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03

MANUFACTURING METHODS FOR CUTTING, MACHINING AND DRILLING COMPOSITES

VOLUME II – TESTS AND RESULTS

GRUMMAN AEROSPACE CORPORATION
BETHPAGE, NEW YORK 11714

AUGUST 1978

FINAL TECHNICAL REPORT AFML-TR-78-103, VOLUME II

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MANUFACTURING TECHNOLOGY DIVISION
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This technical report has been reviewed and is approved for publication.

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High-quality, low-cost manufacturing methods were established for cutting, machining and drilling of composites. Production nondestructive evaluation (NDE) techniques, capable of insuring structural integrity, were also developed. Materials addressed in this program included graphite/epoxy and hybrids/thereof, boron/epoxy, Kevlar/epoxy and fiberglass epoxy. Program highlights are described below.

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Conventional cutting methods were compared to new technology methods such as water-jet, laser and reciprocating cutting. Although the high-speed water-jet and reciprocating cutters worked well with some uncured materials, the slower laser cutter was able to handle all of the materials studied. Steel-rule die blanking was found to be well suited for cutting multiple plies of uncured materials. With regard to cured materials, the water-jet could effectively cut graphite/epoxy, Kevlar/epoxy and fiberglass/epoxy, while the low-power (250 watts) laser could effectively cut only Kevlar/epoxy. The feasibility of producing preplaced holes by blanking was demonstrated and verified by tensile tests.

Several, new low-cost techniques were established for drilling of graphite/epoxy and hybrids thereof. High-speed (21,000 rpm) drilling of graphite/epoxy doubled the life of solid carbide tools. The use of ultrasonic adapters on portable drilling units increased drill life by 100 percent with graphite-boron/epoxy hybrids. Tool geometries that can be successfully applied to Kevlar/epoxy were established. New cutting tool designs for inserted-compacted diamond tools were generated.

Operating paramcters were established for routing, trimming, beveling, countersinking and counterboring. In general, diamond-cut carbide router bits were effective for routing and trimming graphite/epoxy and fiberglass/epoxy. Diamond-chip and opposed-helix router bits had to be used to cut boron/epoxy and Kevlar/epoxy, respectively. Modification of the countersink relief and rake angles substantially improved tool life (from 50 to 300 holes) when drilling graphite/epoxy.

A comprehensive review of all available NDE techniques that could be applied to the inspection of cut, drilled and machined composites was made. The most effective technique that could reliably be applied in a low-cost production mode was tracer fluoroscopy. A prototype, automated inspection system was developed and evaluated under simulated production conditions to facilitate integration of the system with the manufacturing process. Projected time savings for the approach compared to that for manual techniques exceeded 80 percent.

FOREWORD

This Final Technical Report covers the work performed under Contract No. F33615-76-C-5280 for the contract period of 2 August 1976 through 2 August 1978. This contract with Grumman Aerospace Corporation, Bethpage, New York, was initiated under Manufacturing Methods Project No. 322-6, "Manufacturing Methods for Cutting, Machining, and Drilling of Composites". The work was administered under the technical direction of Mr. Paul Pirrung/AFML/LTN, Non-Metals/Composites Branch, Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The Composites Machining Handbook, Volume I, is a concise summary of program results and recommendations. A comprehensive discussion of the overall program is contained in Volume II, Tests and Results.

The program was directed by Mr. Warren Marx, Project Manager. Others assisting on the project were Mr. Sidney Trink, Principal Investigator, of Advanced Materials and Processes Development, Mr. Jack Jenkins and Mr. Leonard Ober of Manufacturing Technology, and Mr. Alfred Weyhreter of Quality Control.

The cooperation and assistance rendered by the following personnel are hereby acknowledged: Mr. John J. Connelly, Arvey Corporation; Mr. John B. Cheung and Mr. G. H. Hurlburt, Flow Research, Inc.; Mr. Roger Arel, Gerber Garment Technology, Inc.; Mr. Thomas J. Labus, IIT Research Institute; Mr. Edward More, Hamilton Standard Division of United Aircraft Corp.; Mr. Gary Jacaruso, Sikorsky Aircraft Division of United Aircraft Corp.; Mr. Ray Koladycz, Camsco, Inc.; Mr. Gerald K. Faaborg, McCartney Manufacturing Co.; Mr. Frank J. Penoza, Pen Associates, Inc.; Daniel Ford and Mr. William Hoyt, TFI Corp.; and Mr. Conrad M. Banas, United Technology Research Center.

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Section 1

SUMMARY

High-quality, low-cost manufacturing methods were established for cutting, machining and drilling of composites. Production nondestructive evaluation (NDE) techniques, capable of insuring structural integrity, were also developed. Materials addressed in this program included graphite/epoxy and hybrids/thereof, boron/epoxy, Kevlar/epoxy and fiberglass/epoxy. Program highlights are described below.

Conventional cutting methods were compared to new technology methods such as water-jet, laser and reciprocating cutting. Although the high-speed water-jet and reciprocating cutters worked well with some uncured materials, the slower laser cutter was able to handle all of the materials studied. Steel-rule die blanking was found to be well suited for cutting multiple plies of uncured materials. With regard to cured materials, the water-jet could effectively cut graphite/epoxy, Kevlar/epoxy and fiberglass/epoxy, while the low-power (250 watts) laser could effectively cut only Kevlar/epoxy. The feasibility of producing preplaced holes by blanking was demonstrated and verified by tensile tests.

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Operating parameters were established for routing, trimming, beveling, countersinking and counterboring. In general, diamond-cut carbide router bits were effective for routing and trimming graphite/epoxy and fiberglass/epoxy. Diamond-chip and opposed-helix router bits had to be used to cut boron/epoxy and Kevlar/epoxy, respectively. Modification of the countersink relief and rake angles substantially improved tool life (from 50 to 300 holes) in graphite/epoxy laminates.

A comprehensive review of all available NDE techniques that could be applied to the inspection of cut, drilled and machined composites was made. The most effective technique

that could reliably be applied in a low-cost production mode was tracer fluoroscopy. A prototype, automated inspection system was developed and evaluated under simulated production conditions to facilitate integration of the system with the manufacturing process. Projected time savings for the approach compared to that for manual techniques exceeded 80 percent.

Section 2

INTRODUCTION

Advanced composites such as boron and graphite fibers in epoxy matrices are now fully qualified and accepted materials for safety-of-flight components. The inherent structural efficiency of these materials led initially to selective application of advanced composites in current aircraft designs and promises to result in even greater use in future advanced technology vehicles. However, these new material forms do not necessarily adapt to the same technology methods used for their predecessor metallic structures. As such, new cost drivers are associated with advanced composite fabrication.

One of the high-cost centers identified with composites manufacturing is the cost of cutting, machining, and drilling at both the detail and assembly levels. Past efforts were successfully applied to reduce the cost of machining boron/epoxy and boron/epoxy-titanium structures. There was considerable room for improvement, however, in the cost and quality of machining graphite/epoxy and graphite/epoxy hybrids. In addition, a number of new machining and cutting techniques have become available over the past few years which offer the potential for innovation and further cost reductions in these operations.

The purpose of this program was to establish production equipment, tooling, and process requirements which would make possible low-cost trimming, machining, and drilling of graphite/epoxy materials and hybrids thereof. In addition, an approach to automated inspection was also to be developed. Specifically, this program addressed the following four distinct areas of effort:

- Cutting of both cured and uncured composites with conventional and advanced technology methods
- Drilling technology as applied to detailed part and assembly fabrication
- Machining technology for routing, trimming, beveling, countersinking and counterboring
- Nondestructive evaluation (NDE) as a production process.

Section 3

GENERAL PROGRAM CONSIDERATIONS

Boron and graphite fibers in epoxy matrices are now fully qualified and accepted materials for safety-of-flight components. The materials selected for use in this program and their relationship to the processes being evaluated are shown in Figures 3-1 and 3-2. The selection uses the B-1 horizontal stabilizer as a baseline and includes hybrid combinations and assembly drilling combinations to be encountered in the Air Force Advanced Tactical Fighter (ATF), as well as situations encountered in fabricating the F-16 vertical fin, the A-7 composite wing structure, the L-1011 vertical fin, and the B-1 vertical fin. The program used panels made from graphite/epoxy tape for baseline testing. The Kevlar/epoxy and fiberglass/epoxy hybrids are representative of material requirements in both the Air Force (ATF) and the NASA L-1011 vertical fin structures. Kevlar is also being considered for use on external plies to improve impact resistance of ATF accessory panels and doors. The baseline materials used in the program include Avco 5505-III-F boron/epoxy, Hercules 3501-5A/A-S graphite/epoxy, Kevlar 49-CS3481/CS800 preimpregnated cloth, and Hexcel F161-7781(E) fiberglass/epoxy.

	MATERIAL	THICKNESS, IN.	HYBRID	PHASE I – CUTTING						PHASE II – DRILLING		PHASE III – MACHINING				
				RADIAL SAW	BAND SAW	LASER	WATER JET	RECIPO-CUTTING	BLANKING	DRILL	REAM	C'SINK	C'BORE	ROUTE	BEVEL	TRIM
BASELINE COMPONENTS	GRAPHITE/EPOXY	1/16			√	√	√	√	√					√		√
	GRAPHITE/EPOXY	1/4		√	√		√			√	√	√	√	√	√	√
	GRAPHITE/EPOXY	1/2		√	√		√			√						
	BORON/EPOXY	1/8		√	√		√	√	√			√	√	√	√	√
	XEVLAR/EPOXY	1/8		√	√	√	√	√	√	√		√	√	√		√
	FIBERGLASS/EPOXY	1/8		√	√	√	√	√	√	√		√	√	√	√	√
HYBRID COMPONENTS	GR/EP + B/EP	1/16	70% GR/EP 30% B/EP		√	√	√			√				√		√
	GR/EP + B/EP	1/4	60% GR/EP 40% B/EP	√	√		√			√	√	√		√	√	√
	GR/EP + B/EP	1/2	50% GR/EP 50% B/EP	√	√		√			√	√	√	√	√	√	√
	GR/EP + KEVLAR/EP	1/16	70% GR/EP 30% K/EP	√	√	√	√							√		√
	GR/EP + KEVLAR/EP	1/4	50% GR/EP 50% K/EP	√	√		√			√		√	√	√		√
	GR/EP + FIBERGLASS/EP	1/16	40% GR/EP 60% FG/EP	√	√	√	√					√		√		√
	GR/EP + FIBERGLASS/EP	1/4	40% GR/EP 60% FG/EP	√	√		√			√		√	√	√	√	√
ASSEMBLY COMBINATIONS	GRAPHITE/EPOXY + BORON/EPOXY TITANIUM	1/2 1/2								√	√					
	GRAPHITE/EPOXY + ALUMINUM	1/2 1/4								√	√					
	GRAPHITE/EPOXY + FIBERGLASS/EPOXY	1/4 .010								√						
	GRAPHITE/EPOXY + TITANIUM	1/8 .020								√	√					
	GRAPHITE/EPOXY + ALUMINUM	1/4-1/2 .020								√						

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Figure 3-1 Program Test Matrix

	Phase I				
	CUTTING				HOLE PREPLACEMENT
MATERIAL	LASER	WATER JET	MECH CUTTER	STEEL RULE DIE	PIERCING
GRAPHITE/EPOXY	√	√	√	√	√
BORON/EPOXY	√	√	√	√	√
KEVLAR/EPOXY	√	√	√	√	
FIBERGLASS/EPOXY	√	√	√	√	
GR/EP + KEVLAR/EPOXY					√

Figure 3-2 Uncured Composite Test Matrix

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Section 4

PHASE I - CUTTING

The objective of this program was to establish low-cost improved manufacturing methods for the cutting of cured and uncured composite materials. The basic combinations evaluated in this phase are shown in Figures 3-1 and 3-2. The materials represent present and next-generation structural design requirements.

4.1 TASK 1 - CONVENTIONAL CUTTING OF CURED COMPOSITES

One of the limiting factors in cutting advanced composite laminates is the effect of out-of-plane cutting forces on breakout at the exit surface. Stationary and portable radial sawing and bandsawing were studied to determine the effect of process parameters on quality and cost. These conventional techniques were studied to provide a baseline against which alternative or high-technology process could be compared.

Radial sawing is generally used in production for straight-line cuts. Its most important advantage is that portable tools can be used. Other advantages of this cutting method are finished cuts, commercially available equipment and tools, and no major capital investment. Process limitations are that only straight cuts can be made and the process is controlled manually. Quality and rate, therefore, are functions of the mechanical capability of the personnel.

Bandsawing is generally used as a rough trimming operation prior to routing and/or routine sanding. The principal advantages of this process are the availability of commercial equipment and its ease of use in cutting patterns. Bandsawing has its limitations, though. It is only a rough cutting process, is dependent upon operator skill, is not amenable to sharp radius cutting, and requires a secondary operation.

4.1.1 Stationary Radial Sawing

Cutting tests were performed on the radial saw shown in Figure 4-1. Repeatable feeds were obtained by attaching a variable drive to the saw cross-slide. A load cell with digital readout was also used to monitor the effects of process variables. A general arrangement of this test set-up is shown in Figure 4-2. Radial sawing tests

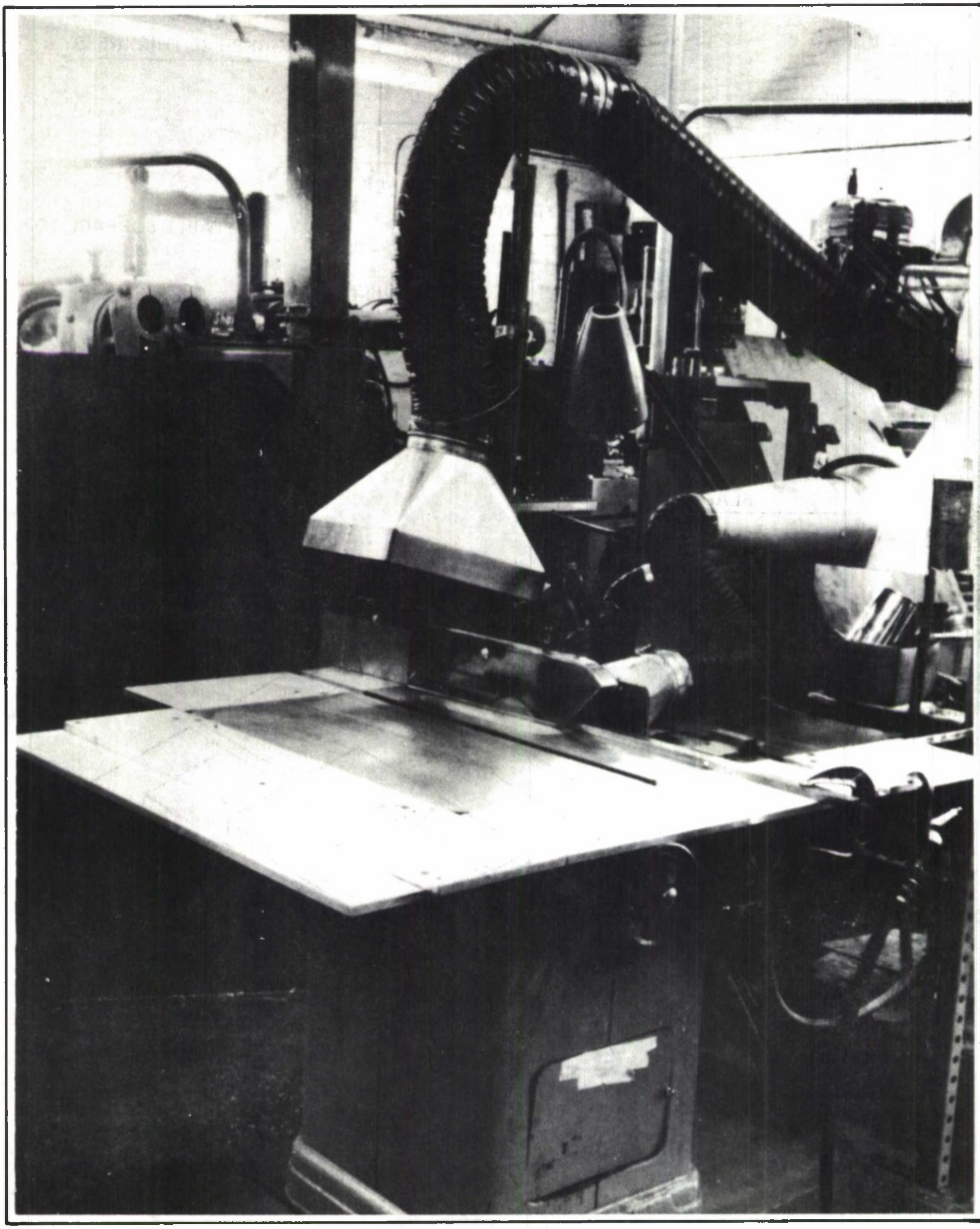

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Figure 4-1 Radial Saw Used in Initial Cutting Tests

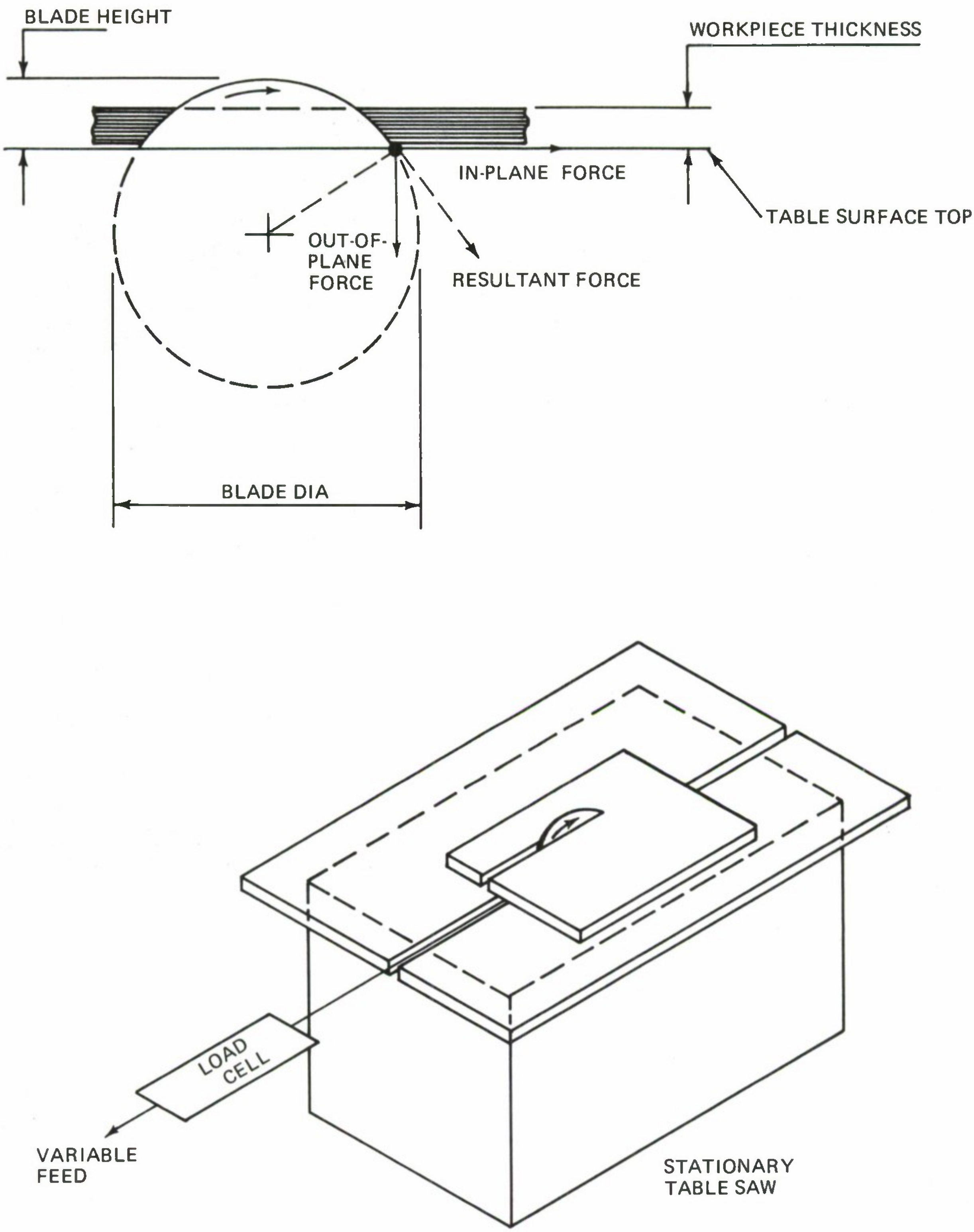

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Figure 4-2 General Arrangement for Radial Sawing Test

were designed to evaluate the effects of blade material and configuration, blade extension above the workpiece, cutting speed and coolant upon feed rate, cut quality, and tool life. The following blade materials and configurations were evaluated:

4.1.1.1 Blade No. 1 - eight-inch-diameter diamond-plated (0.090-inch thick by 0.060-inch wide), circular saw with 60-grit particle size and electro-plated nickel bond. This blade was free-cutting because the 0.008-inch-diameter diamond grit was exposed more than other materials (50 percent extending out from the bond). The blade was made by Sample Marshall Laboratories, Inc.

4.1.1.2 Blade No. 2 - tungsten-carbide, 6.5-inch-diameter, circular saw with a medium grit. This blade was made by Remington Arms Company, Inc.

4.1.1.3 Blade No. 3 - same as Blade No. 1 except that the edges were ground to remove diamond-grit peaks.

4.1.1.4 Blade No. 4 - eight-inch-diameter, hollow-ground, high-speed steel circular saw with 126 straight-backed teeth at a five-degree positive hook. This blade was made by the Simonds Saw and Steel Company.

4.1.1.5 Blade No. 5 - ten-inch-diameter, alternate, square carbide, 100-tooth blade.

Baseline testing was performed using Blade No. 3 with a minimal 0.25-inch blade extension through the workpiece, Excellent cut quality was obtained for all cuts as summarized in Figure 4-3. Wear characteristics were also determined during the baseline tests by measuring blade diameter at appropriate intervals. Results are presented in Figure 4-4. Diametrical wear rates of about 0.001 and 0.008 inch per 100 square inches of cross-sectional area cut were obtained for both graphite/epoxy and fiberglass/epoxy panels, and boron/epoxy panels, respectively.

Extending the blade from 0.25 inch to 1.75 inches beyond the workpiece effectively increased the in-plane forces (compared to those used in the baseline tests). It appeared at first that loading was increased by a factor of three to five. Additional tests, however, showed that a substantial part of the increase was due to tool wear. The actual increase in loading was only about 1.5 times the baseline loading. Cuts made with this blade extension had the same quality, width variation, and exit

MATERIAL	THICK, IN.	BASELINE – BLADE NO. 3 EXCEPT AS NOTED (0.25 BLADE EXTENSION) (NOTE 4)					1.7-INCH EXTENSION OF BLADE NO. 3 (NOTES 2 & 4)					NO COOLANT (BLADE NO. 3)					ROUND-HEAD DIAMOND BLADE NO. 1 (NOTES 4 & 5)					OTHER BLADE CONFIGURATIONS (NOTE 4)					HIGHER CUTTING SPEED ROUND-HEAD DIAMOND BLADE NO. 1 (NOTES 4, 5, 7)				
		FEED, (IPM)	LOAD, (LB)	CUT WIDTH, TOL (IN.)	RMS	CUT QUALITY	FEED, (IPM)	LOAD (LB)	CUT WIDTH, TOL (IN.)	RMS	CUT QUALITY	FEED, (IPM)	LOAD, (LB)	CUT WIDTH, TOL (IN.)	RMS	CUT QUALITY	FEED, (IPM)	LOAD, (LB)	CUT WIDTH, TOL (IN.)	RMS	CUT QUALITY	FEED, (IPM)	LOAD, (LB)	CUT WIDTH, TOL (IN.)	RMS	CUT QUALITY	FEED, (IPM)	LOAD, (LB)	CUT WIDTH, TOL (IN.)	RMS	CUT QUALITY
GRAPHITE/EPOXY	1/4	68.6	5.50	0.010	16-32	GOOD						24.4	6.20	0.0035	16	GOOD	68.6	3.25	0.007	63	POOR	20.0 (NOTE 1)	4.75	0.0035	32-63	FAIR	68.6	7.07 (NOTE 8)	.006	63	POOR
	1/2	32.2	6.75	0.005	16-32	GOOD	24.4	13.9	0.006	16	EXC																32.2	7.49 (NOTE 8)	.0019	63	POOR
HYBRID GRAPHITE BORON/EPOXY	1/2 (1/4-1/4)	13.8	3.68	0.005	32	GOOD	13.8	5.60	0.002	32	GOOD	24.4	10.30	0.0095	32-63	FAIR	13.8	3.2	0.002	32	GOOD						13.8	3.59	.005	32	GOOD
BORON/EPOXY	1/8	93	5.50	0.005	16-32	GOOD																					102	3.35	.003	63	POOR
KEVLAR/EPOXY	1/8	43.6 (NOTE 3)	6.30	0.004	16	EXC																32.2 (NOTE 6)	1.5	0.009	7250	POOR					
FIBERGLASS/ EPOXY	1/8	68.6	5.10	0.005	16-32	GOOD																									

NOTES:

1. BLADE NO. 2, TUNGSTEN CARBIDE COATED, 6.5-INCH DIAMETER MEDIUM GRIT (5790 SFM)
2. BLADE NO. 3, DIAMOND COATED, 60 GRIT, SIDES GROUND, 8-INCH DIAMETER (7154 SFM)
3. BLADE NO. 4, HIGH-SPEED STEEL, 126 STRAIGHT-BACKED TEETH, 8-INCH DIAMETER (7154 SFM), BLADE RUN BACKWARDS
4. COOLANT USED
5. BLADE NO. 1 SAME AS BLADE NO. 2, EXCEPT THAT SIDES WERE NOT GROUND
6. ALTERNATE, SQUARE CARBIDE, 100 TEETH, 10-INCH DIAMETER (8942 SFM)
7. SURFACE SPEED = 11,362 SFM
8. FOR EQUIVALENT BLADE WEAR, LOADS FOR HIGHER CUTTING SPEEDS ARE LESS

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Figure 4-3 Summary of Stationary Radial Sawing Tests

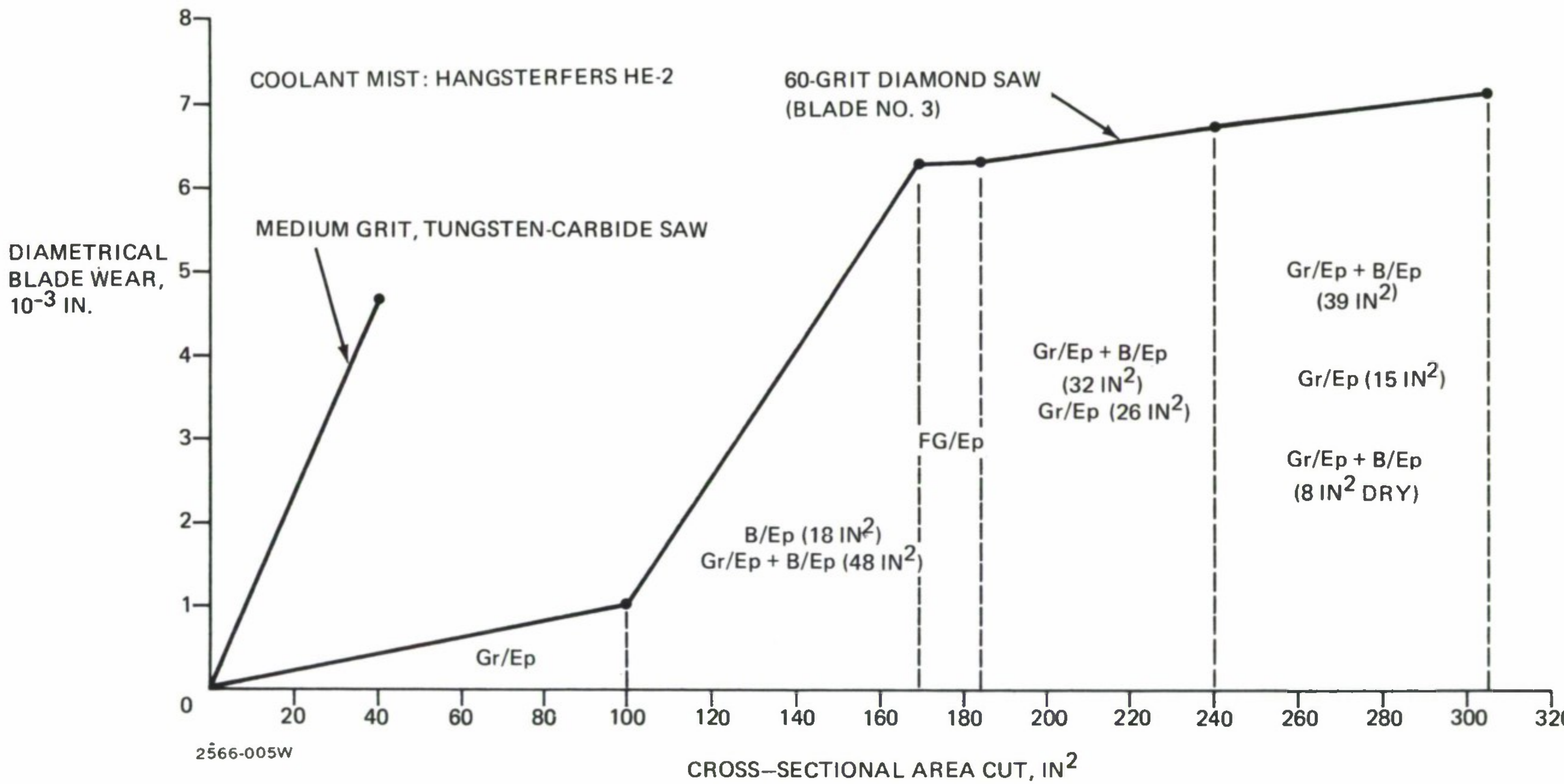

Figure 4-4 Blade Wear as a Function of Material and Area Cut

breakout as the baseline cuts. The measured increase in in-plane force was apparently not sufficient to affect cut quality.

Radial saw cuts of graphite/epoxy without coolant had the same cut quality as the baseline cuts. Sawing of hybrid boron-graphite/epoxy without a coolant, however, gave increased roughness readings and wider width variations. As expected, limited data indicated that blade life was extended by using a coolant.

Use of a round-head blade (No. 1) that was not side-ground did not affect the cutting force. Although surface roughness was increased, exit breakout quality was the same as that for the baseline cuts.

Cutting tests using a tungsten-carbide saw (Blade No. 2) to cut 0.31-inch-thick graphite/epoxy panels showed that cutting forces were three times greater than those encountered with the 60-grit diamond-plated blade. Equivalent diameter tool wear was found to be twelve times greater than that of a diamond blade.

Kevlar/epoxy baseline cuts were made with an 8-inch-diameter, high-speed steel (HSS) blade (No. 4) with 126 straight-backed teeth. This blade was run in reverse at 7154 surface feet per minute (sfm). All surface finish readings were taken with a comparison scale. Exit breakouts on all baseline specimens were clean, that is, the outside fibers and peel-ply layers were not lifted. Cuts made with the blades extended 1.7 inches had the same quality, width variation and exit breakout as the baseline cuts. The measured increase in the in-plane force was apparently not sufficient to affect cut quality. Conventional cutting of Kevlar/epoxy with Blade No. 3 and a 60-tooth carbide-tipped blade gave cuts with a fuzzy edge.

High-speed cutting tests at 11,300 sfm were also evaluated, using Blade No. 1 on graphite/epoxy, boron/epoxy, and graphite-boron/epoxy hybrids (see Figure 4-3). In general, these tests showed that cut quality was unchanged. When compared to previous tests conducted with the round-head diamond Blades No. 1 and 3 at 7154 sfm, tool life and cutting forces decreased slightly for graphite/epoxy and boron/epoxy laminates during the high-speed (11,362 sfm) evaluation. Comparison of quality of cut was performed against identical feed conditions at low speed (7154 sfm) using the same blade. As shown in Figure 4-3, the rms values for high- and low-speed tests were consistent. Tool wear (Figure 4-5) was 76 percent greater for boron-reinforced laminates than that experienced by Blade No. 3 at lower speeds after an equivalent amount of cutting.

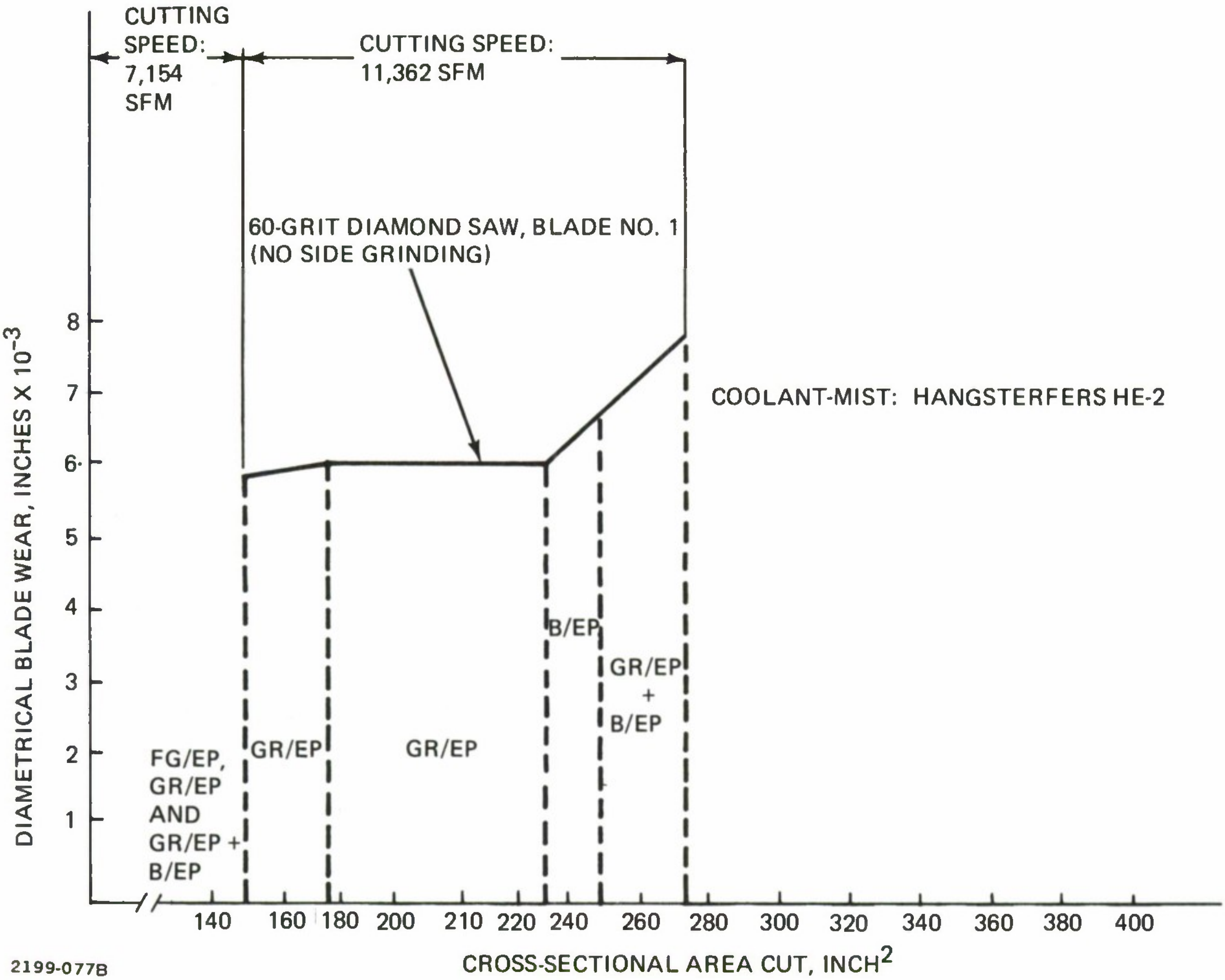

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Figure 4-5 Effect of Material and Area Cut on Blade Wear

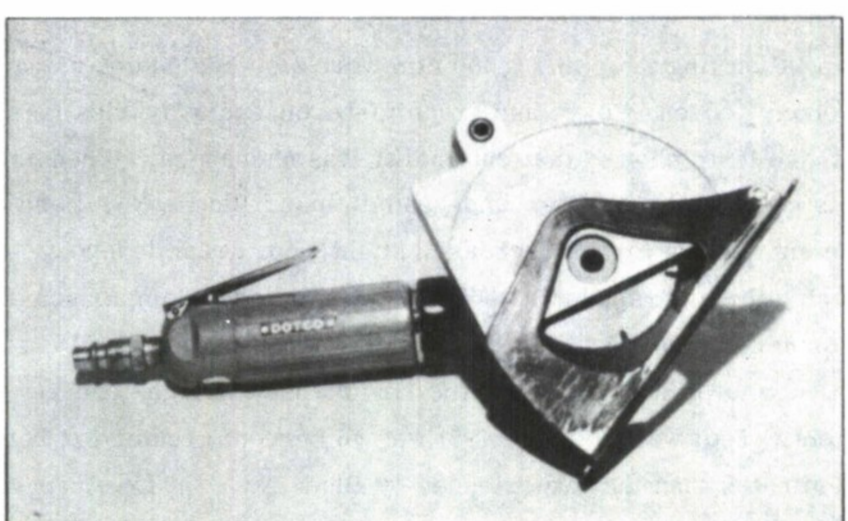

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Figure 4-6 Portable Radial Saw

4.1.2 Portable Radial Sawing

Portable radial sawing tests were conducted to determine the effect of cutting tool type and geometry on feed-rate and cut quality (as measured against a previously established baseline for stationary radial sawing). Cutting tests were performed with the portable radial saw shown in Figure 4-6. The air-driven Dotco saw operates at 9500 rpm and utilizes a 3-inch-diameter blade. Cutting test results for cured composites are summarized in Figure 4-7.

4.1.2.1 Cutting Blades - The same blade construction (60 grit, diamond plate) used for stationary radial sawing of graphite/epoxy, boron/epoxy, and fiberglass/epoxy was found acceptable for portable sawing. The HSS hollow-ground circular saw blade used for Kevlar/epoxy was not available in the 3-inch portable size diameter. In its place, the most acceptable blade (No. 13) was found to have 12 carbide-tipped teeth with 20-degree alternating face bevels (Figure 4-8).

An alternative method for cutting Kevlar/epoxy laminates involved use of a blade similar to the one used in the stationary radial saw tests. This blade, an 8-inch-diameter, high-speed-steel type with 126 straight-backed, hollow-ground teeth, was run in reverse. A 3-inch-diameter blade with 47 teeth would have to be used with the Dotco portable saw. This blade would have to be specially prepared because it is not available commercially. However, if an electric-powered saw with a 6- to 8-inch-diameter blade were used, it would then be possible to utilize the hollow-ground, straight-backed-tooth blade.

4.1.2.2 Tool Life - Diametrical wear for diamond blade portable radial sawing is shown in Figure 4-9. Initial wear on a new, diamond-coated blade generally occurred at a relatively high rate due to rounding of the exposed sharp edges. This also occurred when cutting cured boron/epoxy and hybrid boron-graphite/epoxy laminates. However, the wear rate was considerably lower when cutting cured graphite/epoxy and fiberglass/epoxy panels. As expected, there appeared to be a trend that spray coolant application extended cutter life. The 12-tooth carbide-tipped blade with alternating face bevel used on Kevlar/epoxy was designed to enable the teeth to draw the edge fibers downward into the laminate as the cutting action occurred (Reference 1). Although this blade produced the cleanest cut (least amount of fabric fraying), its cutting edges dulled rapidly.

MATERIAL	THICKNESS INCH	SPEED RPM	CUTTING RATE SFM	CODLANT (5)	BLADE NUMBER (1)	AREA CUT IN^2	FEED RATE IPM	DIMETRAL WEAR INCH	EDGE QUALITY RMS	EDGE QUALITY RATING
BORON/EPOXY	0.136	9500	7496	NONE	8	5.0	53.5	0.002	16-32	GOOD
GRAPHITE/EPOXY + BORON/EPOXY	0.337	9500	7496	NDNE	8	11.9	42.7	0.0008	16-32	GDOD
GRAPHITE/EPOXY	0.267	9500	7496	NONE	9	58.8	58.8	0.005	32	GOOD
GRAPHITE/EPOXY + FIBERGLASS/ EPOXY	0.260	9500	7496	NONE	9	9.4	61.1	0.0001	32-63	FAIR
GRAPHITE/EPOXY + BORON/EPOXY	0.333	9500	7496	NONE	9	11.74	42.9	0.002	16-32	GOOD
GRAPHITE/EPOXY	0.067	9500	7496	NONE	9	2.2	132	0.0001	63	FAIR
GRAPHITE/EPOXY + BORON/EPOXY	0.090	9500	7496	NONE	9	32	88	0.0007	125	POOR
GRAPHITE/EPOXY + KEVLAR/EPOXY	0.0635	9500	7496	NONE	9	2.3	98	0.0001	> 125	POOR (2)
GRAPHITE/EPOXY + KEVLAR/EPOXY	0.302	9500	7496	NONE	9				> 125	POOR (2,3)
GRAPHITE/EPOXY + FIBERGLASS/ EPOXY	0.064	9500	7496	NONE	10	2.3	166	0.002	63	FAIR' FUZZY
FIBERGLASS/EPOXY	0.147	9500	7496	NONE	10	5.3	100	0.0004	32	GOOD
BORON/EPOXY	0.135	9500	7496	NONE	7B	5.0	96	0.005	16-32	GOOD
GRAPHITE/EPDXY	0.275	9500	7496	NONE	7B	10.0	46	0.000	16-32	GOOD
KEVLAR/EPOXY	0.112	9500	7496	NONE	11	2.7	96		> 125	POOR, FUZZY (1)
KEVLAR/EPOXY + GRAPHITE/EPOXY	0.271	9500	7496	NONE	11	6.5	29		> 125	POOR, FUZZY (4)
KEVLAR/EPOXY	0.112	9500	7496	YES	12	4.0	77	WDRN OUT COM- PLETELY	> 125	PDOR, FUZZY (4)
KEVLAR/EPOXY	0.112	9500	7496	NONE	13	6.7	49	0,010	125	POOR, FUZZY
KELVAR/EPOXY	0.112	9500	7496	YES	13	6.7	49	WEAR	125	PDOR,FUZZY
GRAPHITE/EPOXY + KEVLAR/EPOXY	0.0635	9500	7496	NONE	13	1.5	103	LAND	125	POOR, FUZZY
GRAPHITE/EPOXY + KEVLAR/EPDXY	0,278	9500	749B	NDNE	13	6.7	33		63	FAIR, FUZZY
BDRDN/EPDXY	0.136	9500	7496	YES	14	3.3	64	0.00911	16-32	GOOD
GRAPHITE/EPOXY	0.267	9500	7496	YES	14	6.4	25	0.002	32	GOOD
GRAPHITE/EPOXY	0.570	9500	7496	YES	14	6.8	12	0.002	32	GOOD
GRAPHITE/EPOXY +BORON/EPOXY	0.345	9500	7496	YES	14	8.3	18.5	0.0015	32	GOOD
FIBERGLASS/EPOXY	0.147	9500	7496	YES	14	5.3	44	0.0009	32	GOOD
BORON/EPOXY	0.136	9500	7496	YES	14	3.3	42	0.0009	16-32	GOOD

NOTES

(1)
- BLADE # 8 - 60 - GRIT DIAMOND—PLATED USED SLOTTED AND NOT SIDE-GROUND
- BLADES # 9 AND # 10- 60-GRIT DIAMOND PLATED NEW NOT SLOTTED AND NOT SIDE GRDUND
- BLADE # 7B - 40-GRIT DIAMOND-PLATED NEW SLOTTED AND NOT SIDE-GROUND
- BLADE # 11 - 12-TOOTH ALTERNATE SOUARE BEVELED CARBIDE-TIPPED
- BLADE # 12 - 168-TOOTH HIGH SPEED STEEL MILLING CUTTER
- BLADE # 13 - 12-TOOTH 20° ALTERNATING FACE LEVEL CARBIDE-TIPPED
- BLADE # 14 - 60 GRIT: DIAMOND PLATED, NDT SIDE GROUND

(2) CUT EDGE FUZZY BLADE LOADED-UP WITH KEVLAR/EPOXY

(3) CUTTING NOT POSSIBLE

(4) CUTS UNSATISFACTORY

(5) COOLANT-HAGSTERFERS HE-2 (20 PARTS WATER TO ONE PART HE-2)

2566-006W

Figure 4-7 Summary of Portable (Manual) Radial Sawing of Cured Composites

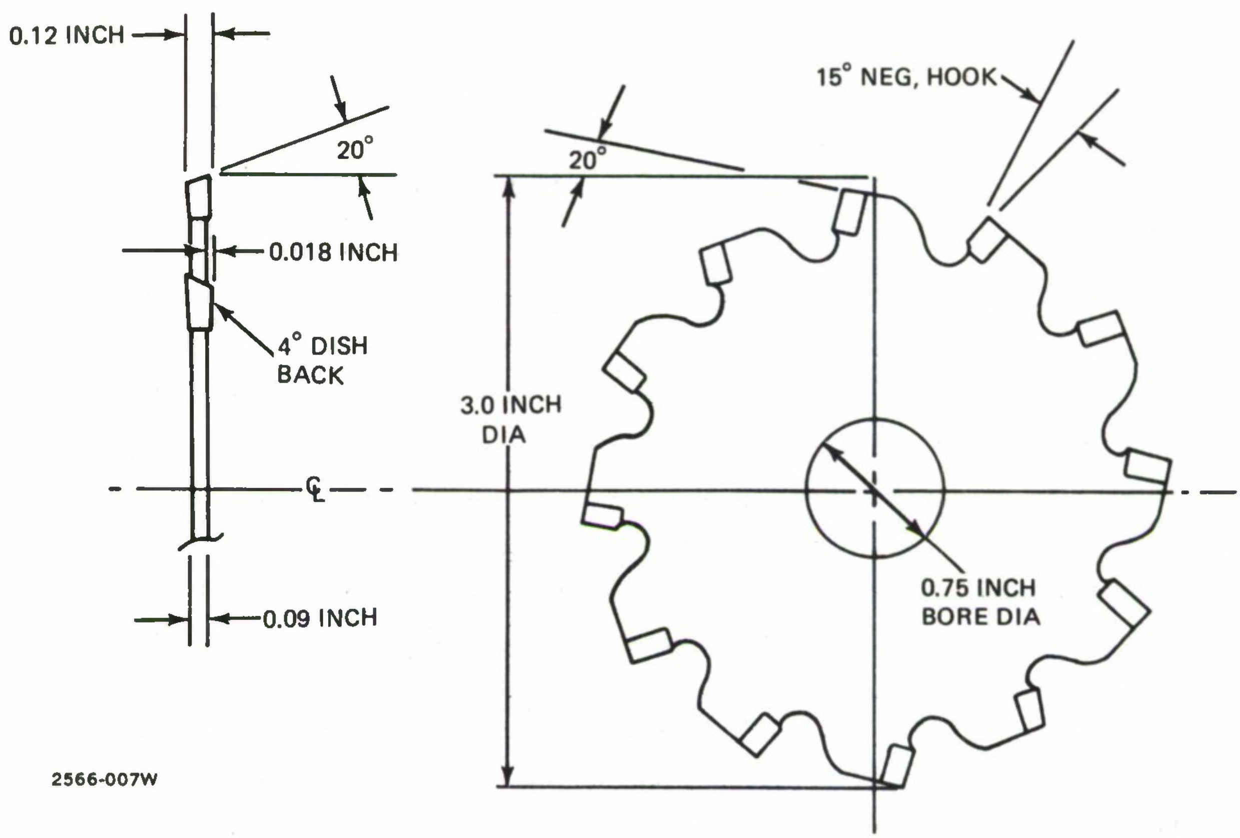

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Figure 4-8 Carbide-Tipped Saw with 12 Teeth (Alternating Face Bevel), Blade No. 13

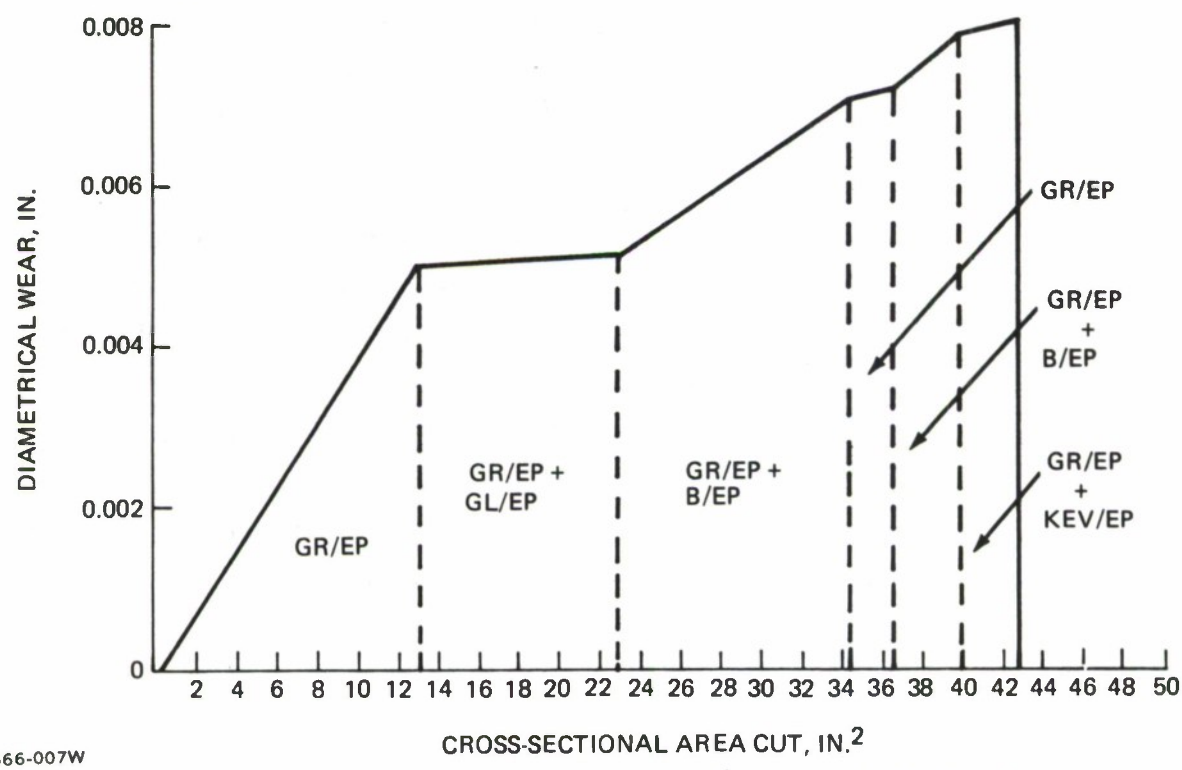

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Figure 4-9 Wear Rate for Portable Radial Sawing with 3-inch Diameter, 60-Grit Diamond Plated Blade (No. 9)

A wear land of 0.010 inch developed on the cutting edges after 22 square inches (cross-sectional area) of laminate had been cut. This amount of wear appears to be the most that could be allowed before resharpening would be necessary. Depending on the frequency of use of these blades, resharpening would probably be required after each day's use. Application of a coolant did not improve cut quality.

4.1.2.3 Edge Quality - Manual radial sawing compares well with stationary radial sawing for cutting basic advanced composite materials such as graphite/epoxy, boron/epoxy and fiberglass/epoxy with a diamond-plated blade. Good quality cuts requiring no post-processing were obtained.

Cutting of Kevlar/epoxy and hybrid Kevlar/epoxy laminates requires special saw blades to eliminate fuzzing. This was demonstrated with a stationary saw using a blade with small, straight-back, hollow-ground teeth run in reverse. Three-inch-diameter blades of this type are not commercially available. Blade No. 12, which was used in those tests, worked well for about 10 inches and then failed. A 12-tooth carbide blade (No. 13) that draws the edge fibers downward into the laminate as cutting progresses, produced the best results in Kevlar/epoxy and Kevlar/epoxy hybrids. However, this edge would require post-process refinement.

4.1.2.4 Cutting Speed - Portable (manual) radial saw cutting speeds approached those obtained with the stationary radial saw for both basic materials (graphite/epoxy and fiberglass/epoxy). A summary plot of feedrate as a function of material thickness is given in Figure 4-10. As the blades become worn, feedrates may drop by 50 percent.

4.1.3 Bandsawing

Bandsawing tests were conducted to evaluate carbon steel blades, tungsten carbide blades and diamond-plated blades for composite cutting. Cutting tests were performed on a Do-All Zephyr friction saw (Figure 4-11). Cutting test results are summarized in Figures 4-12 and 4-13 for each blade type.

4.1.3.1 Carbon Steel Blades - A 10-pitch, 0.5-inch-wide by 15.5-foot-long, raker set was used to cut a 0.6-inch-thick, graphite/epoxy panel. The blade became worn after 12 inches of material had been cut. The remainder of the designated graphite/epoxy cuts were performed with a 32-pitch, 0.25-inch-wide by 9.5-foot-long precision wave set.

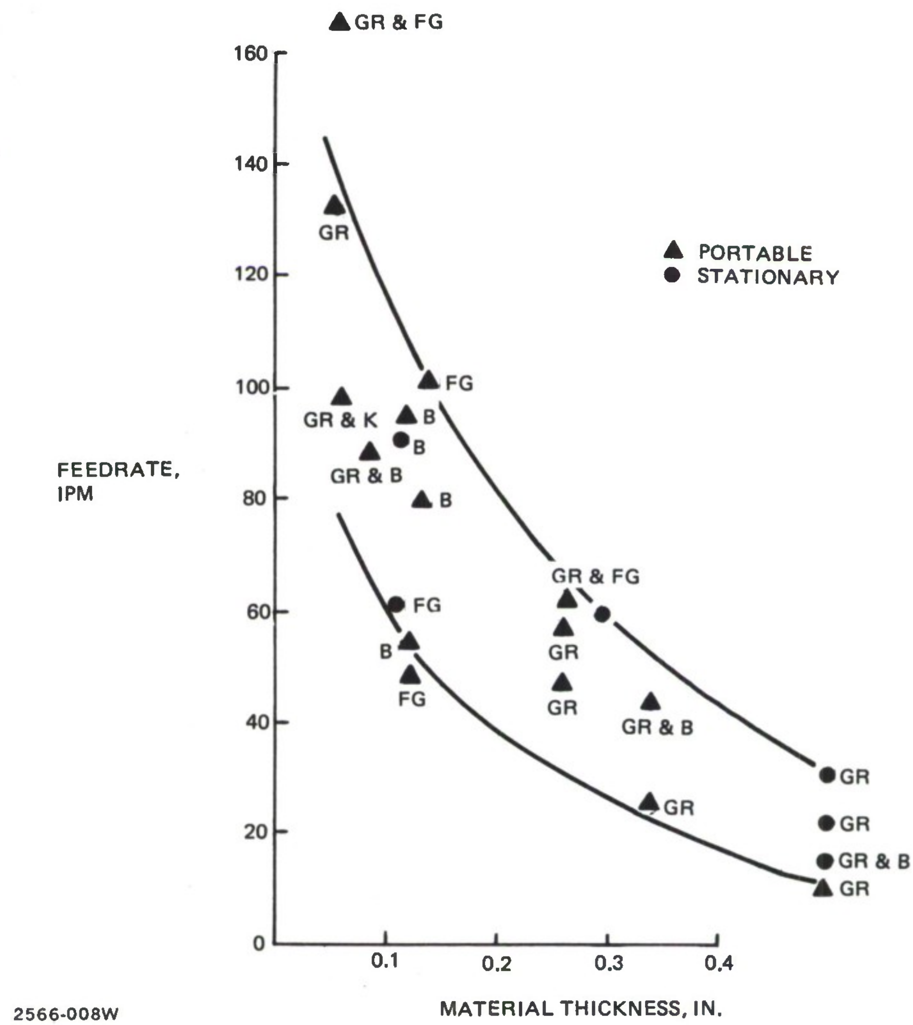

Figure 4-10 Effect of Material Thickness on Radial Sawing Feed Rate

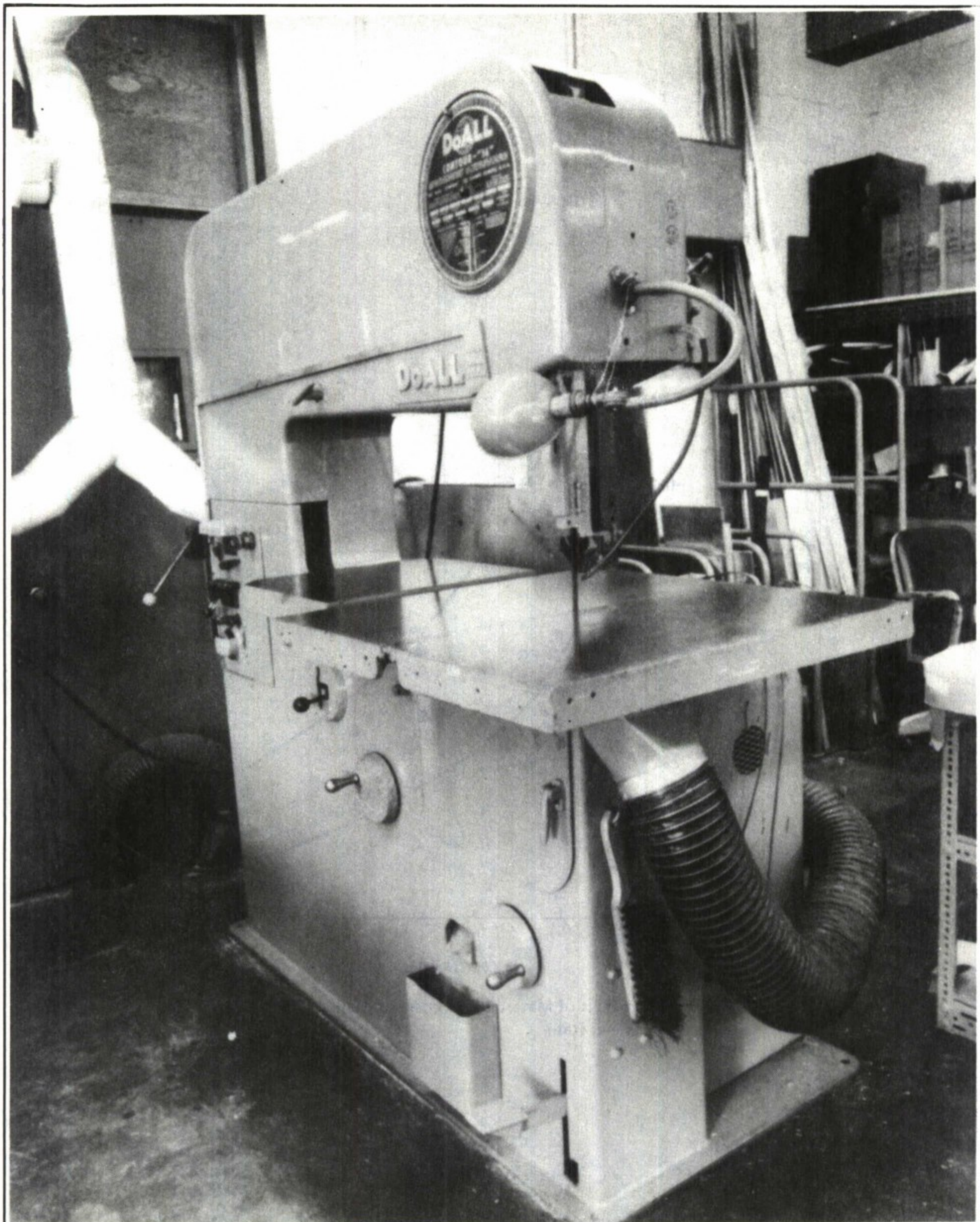

Figure 4-11 Do-All Zephyr Friction Saw

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WORKPIECE		CUTTING SPEED, SFM	HAND FEED	ACTUAL CUTTING RATE, IPM	FINISH, RMS	QUALITY	WEAR, IN. $\times 10^{-5}$
MATERIAL	THICKNESS, IN.						
GR/EP	1/16	2,000	LIGHT	19			
			HEAVY	87	>250	VERY POOR	
			LIGHT	41			
		3,000	HEAVY	122	>250	VERY POOR	
		4,000	HEAVY	175	>250	VERY POOP	
	1/4	4,000	HEAVY	100	SEE FIG. 7-13	SEE FIG. 7-13	
		4,000	LIGHT	20			
		2,000	LIGHT	13	250	POOR	
		2,000	HEAVY	50			
GR/EP+FG/EP	1/16	2,000	LIGHT	24	>250	VERY POOR	
		2,000	HEAVY	133	>250	VERY POOR	
		4,000	LIGHT	150			
		1,000	HEAVY	20			
GR/EP+FG/EP	1/4	1,000	LIGHT	12	250	POOR	
		2,000	LIGHT	17			
		2,000	HEAVY	48	250	POOR	
		4,000	HEAVY	80			9.4
FG/EP	0.143	4,000	LIGHT	20	250	POOR	
	0.143	4,000	HEAVY	80			
KEV/EP	0.118	5,300	LIGHT	16.3	>250	VERY POOR	
GR/EP +KEV/EP	0.065	4,000	LIGHT	29	>250	VERY POOR	
	0.065	2,000	LIGHT	25			
	0.28	4,000	LIGHT	12	>250	VERY POOR	
	0.28	4,000	HEAVY	32			
	0.28	2,000	LIGHT	9	>250	VERY POOR	
	0.28	2,000	HEAVY	21			5.9
GR/EP+ B/EP	0.334	2,000	HEAVY	13	250	POOR	
	0.334	4,000	HEAVY	14	125	GOOD	
	0.334	4,000	HEAVY	14			0.2
	0.334	4,000	HEAVY (WET)	12			0.34

Figure 4-12 Tungsten-Carbide Bandsaw Data Summary

2566-009W

BANDSAW	WORKPIECE		CUTTING SPEED, SFM	HAND FEED	CUTTING RATE, IPM	FINISH, RMS	QUALITY	WEAR, IN. x 10^{-5}
	MATERIAL	THICKNESS, IN.						
60 GRIT DIAMOND BAND SAW	GR/EP	0.270	3,000	LIGHT	8			
		0.270	3,000	HEAVY	16	250	POOR	0.15
	B/EP	0.136	4,000	LIGHT	25	125	GOOD	
		0.136	4,000	HEAVY	86			
	GR/EP+ B/EP	0.091	4,000	LIGHT	34			
		0.091	4,000	HEAVY	120	125	GOOD	
		0.485	2,000	LIGHT	12	125	GOOD	0.14
		0.485	2,000	HEAVY	28			
		0.485	4,000	LIGHT	19	>250	VERY POOR	
		0.485	4,000	HEAVY	33			0.30
		0.485	2,000	LIGHT	13	125	GOOD	
		0.490	2,000	HEAVY (WET)	31			
		0.490	2,000	LIGHT (WET)	13	>250	VERY POOR	0.17
IOT CARBON STEEL BLADE	GR/EP	0.6	500	HEAVY	4.38	125-250	FAIR	BLADE WORN IN 12 INCHES
		0.6	2,000	HEAVY	7			
32T CARBON STEEL BLADE	GR/EP	0.118	2,000	MEDIUM	34	250	POOR	
		0.118	5,400	MEDIUM	55			
		0.118	4,000	MEDIUM	46			
		0.067	2,000	MEDIUM	25	250	POOR	
		0.067	1,000	MEDIUM	12	>250	VERY POOR	
18T CARBON STEEL BLADE NOTE 1	KEV/EP	0.125	5,000	MEDIUM	72	125	GOOD	
NOTE 2		0.125	5,000	LIGHT	90	>250	VERY POOR	
FRICTION	KEV/EP	0.125	7,000	MEDIUM	52	125-250	FAIR	NO SIGNIFICANT WEAR

NOTES

1 - 18-PITCH RAKER – TYPE SAW WITH SOME SET REMOVED AND SAW RUN IN REVERSE DIRECTION
2 - UNMODIFIED 18-PITCH RAKER SAW

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Figure 4-13 Diamond and Carbon Steel Bandsaw Data Summary

The blade became severely worn after 36 inches of material had been cut. As a result, carbon steel blades are considered unacceptable for graphite/epoxy.

It was shown that the preferred method of bandsawing Kevlar/epoxy involved use of a blade with raker set teeth lapped on each side (Figure 4-14). The blade used had 18 teeth per inch. After the blade was inserted into a machine, the teeth were lapped on each side with a fine-grit stone. About 0.005 to 0.010 inch of material was removed, resulting in a flat area parallel to the sides of the blade. The blade was run with the back side of the teeth entering the workpiece. A cutting speed of 5000 sfm and a feed rate of about 72 rpm (relatively fast) produced a good cut. The fuzz that appeared on the edge could be removed by using wet, 400-grit aluminum oxide or silicon carbide abrasive paper.

4.1.3.2 Tungsten Carbide Blades - A Remington, cemented tungsten-carbide, medium-grit blade (114 inches long by 0.5 inch wide by 0.047 inch thick) was used to cut 351 linear inches (67 square inches) of the various materials. As expected, the wear rate when cutting hybrids containing boron/epoxy was about four times greater than that for the other hybrids or baseline materials (Figure 4-15). The Third Quarterly Report for the Advanced Composite Wing Structure Program (Contract No. F33615-68-C-1301) describes carbide-chip bandsaws capable of cutting only 174 linear inches of 0.090-inch-thick boron/epoxy laminates, while the diamond-chip equivalent was still functional after cutting 2,300 inches. These results show the inability of the carbide chips to withstand the abrasiveness of the boron filaments. In addition, the entire saw blade became coated with Kevlar while cutting Kevlar/epoxy panels.

4.1.3.3 Diamond Blades - A diamond-plated bandsaw having a 60-grit particle size and an electroplated nickel bond was used for all cutting tests. The wear rate for cutting a 50-50 mixture of boron/epoxy and graphite/epoxy was 0.001 inch per square inch cut (Figure 4-16). Application of a water coolant had the effect of reducing the wear rate by 40 percent.

4.1.3.4 Quality - The bandsawing operation requires a post-processing operation to establish a finished edge. Measured edge quality and types of flaws are summarized in Figures 4-12 and 4-13, and discussed in Section 7.0.

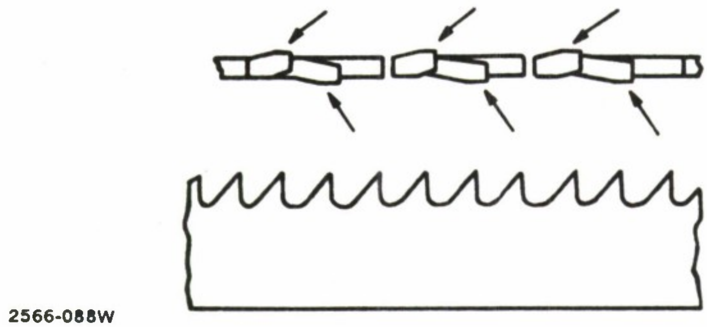

Figure 4-14 Modified Bandsaw Blade for Kevlar/Epoxy

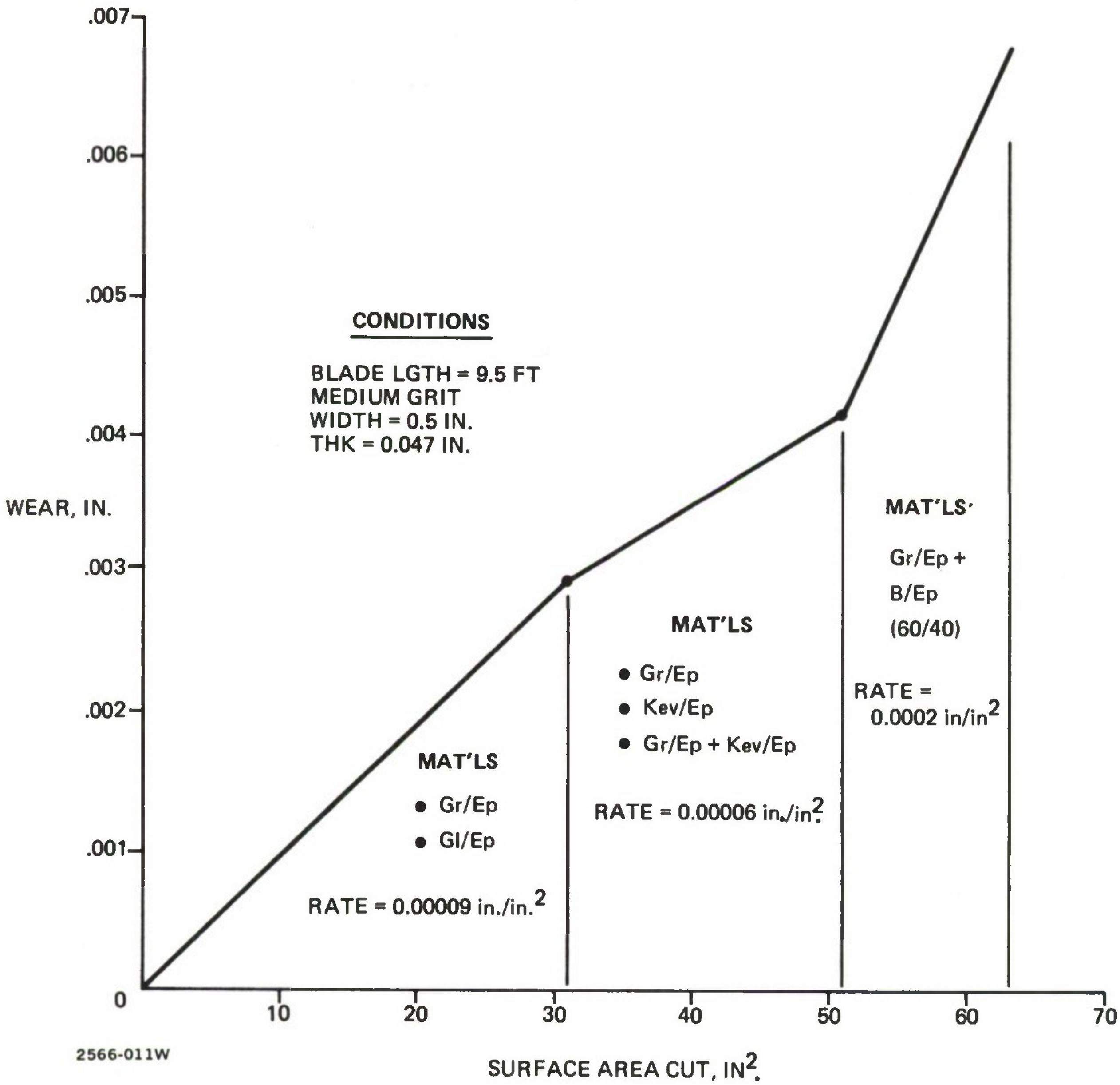

Figure 4-15 Wear Rate for Tungsten-Carbide Bandsaw Blades

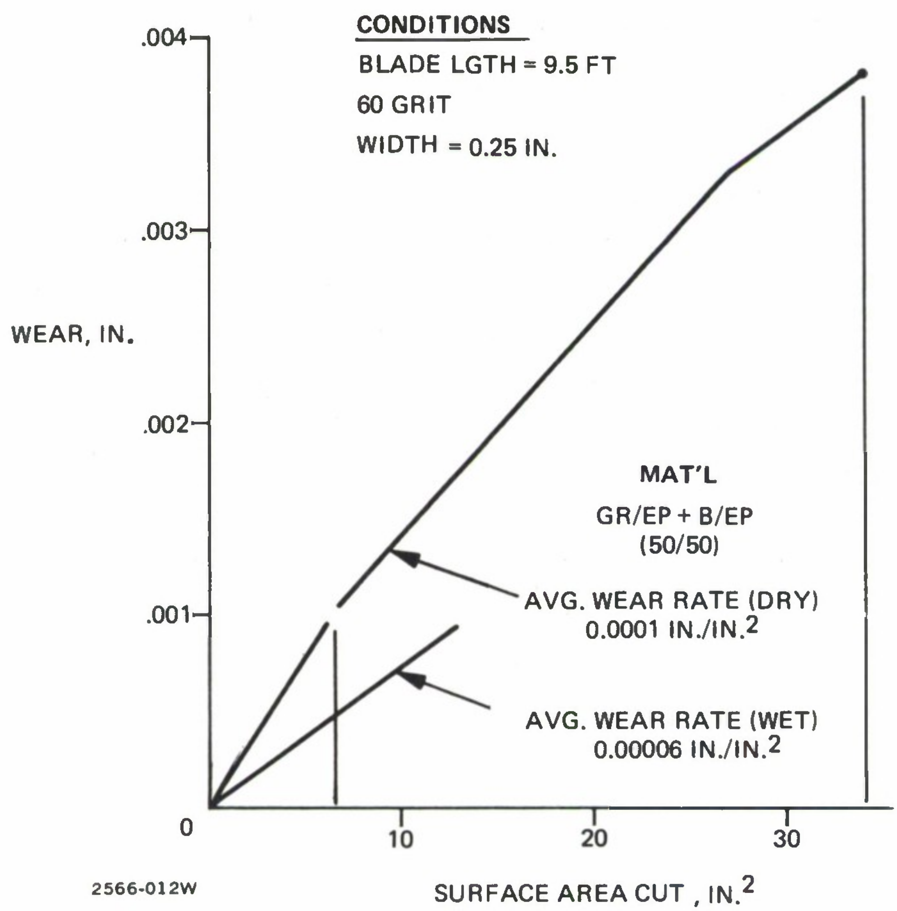

Figure 4-16 Wear Rate for Diamond-Chip Bandsaw Blades

4.2 TASK 2 - CUTTING OF UNCURED COMPOSITES

The conventional approach for cutting uncured composite materials involves manual cutting with a carbide disc cutter, scissors, or power shear. However, several alternate techniques appear to be potentially applicable as substitutes for this costly approach. Four of these techniques evaluated were water-jet cutting, laser cutting, reciprocating mechanical cutting, and steel-rule blanking. All four techniques were evaluated with respect to their ability to cut graphite/epoxy, boron/epoxy, fiberglass/epoxy, and Kevlar/epoxy in the uncured condition.

4.2.1 Water-Jet Cutting of Uncured Composites

This process severs material by forcing water through a small-diameter jet at high velocities. As the water-jet impinges on the surface, it cuts by inducing localized stress failure and eroding the material. Typical cutting conditions are a water-stream diameter of 0.010 inch and water-jet velocities up to 2900 feet per second (fps). A schematic representation of commercially available, water-jet cutting equipment is shown in Figure 4-17. One such system (Flow Industries, Inc.) uses a 30-gpm, variable-volume, pressure-compensated pump that delivers hydraulic oil at pressures up to 3000 psi to the intensifier by a pilot-operated four-way valve. The intensifier utilizes a differential-area, double-acting piston that is shuttled back and forth by the high oil pressure. Attached directly to the main piston are two smaller pistons whose areas are one-twentieth that of the main piston. This arrangement provides the 20-to-1 pressure intensification. Pressurized water flows out of the high-pressure cylinders through a pair of check valves. The water system includes an accumulator that smooths out the pulses produced by the pump. The pressurized water is conveyed through stainless steel tubing to the nozzle from which it is forced out through a synthetic sapphire orifice. A 1/4-inch-diameter tube beneath the nozzle catches the spent water and dust. The basic system capability is 1.5 gpm at 60,000 psi.

The baseline cutting tests were conducted under subcontract by the Flow Research Company (Reference 2). It was found that water-jet cutting performance is affected by jet pressure, nozzle orifice diameter and traverse speed which, in turn, are governed by the type and thickness of the material to be cut. Both cured and uncured, advanced composite materials were water-jet cut with the system shown

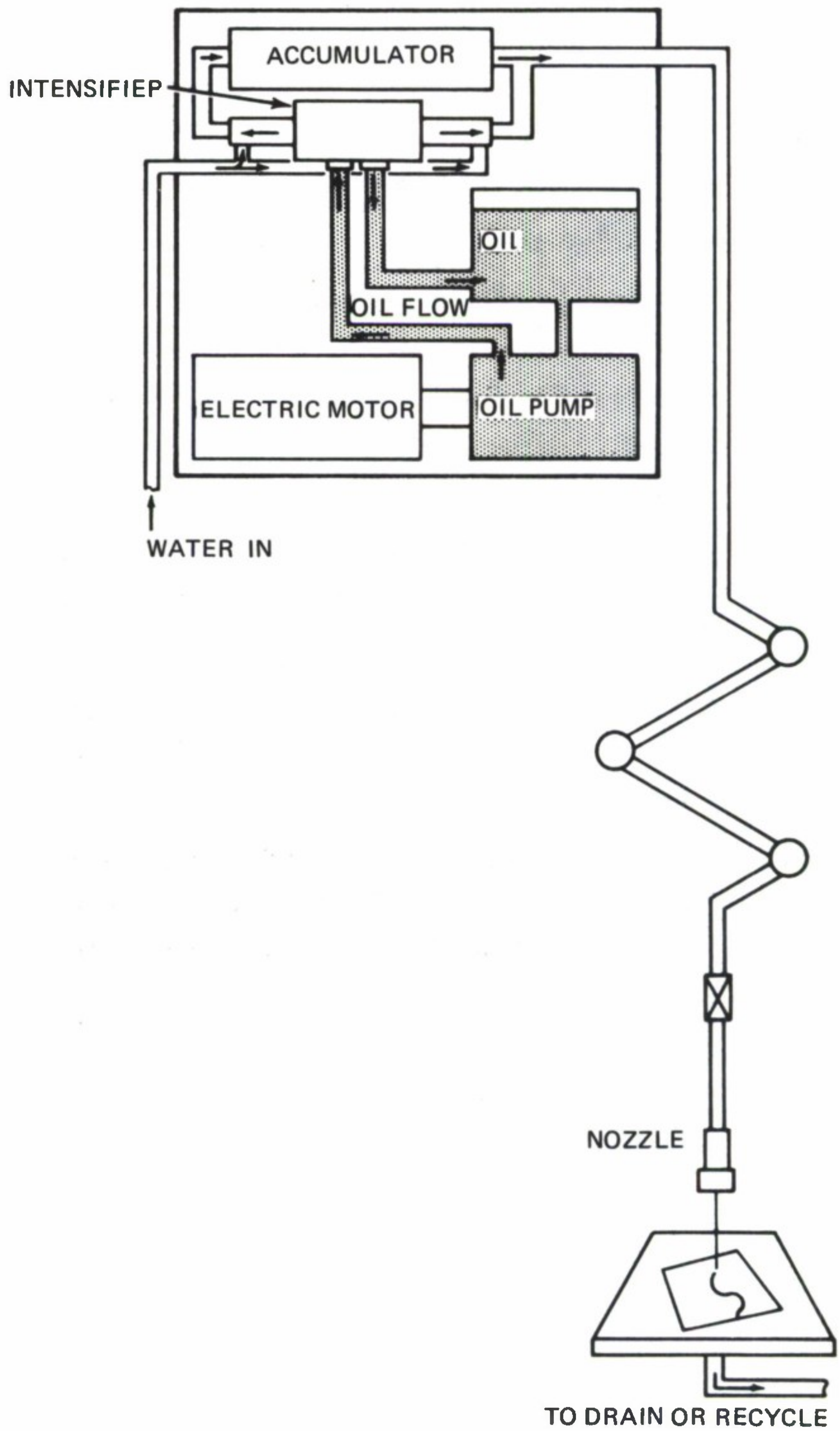

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Figure 4-17 Schematic Representation of High-Pressure Water-Jet Cutting System

in Figures 4-18 and 4-19. A fast-acting hydraulic cylinder moves the sample under the nozzle to effect cutting. Figure 4-19 shows the general arrangement of the traverse table and high-pressure pumping unit.

The uncured materials were cut for the most part in the 90-degree direction (perpendicular to the orientation of the fibers). Cutting in the zero-degree direction would merely be a test of the water jet in cutting the epoxy resin, since the jet would only be moving between the fibers. A summary of the "best cut" water-jet parameters is given in Figure 4-20. Observations made during the cutting tests were:

- The graphite/epoxy samples cut with a good, clean edge finish
- In cutting the boron/epoxy samples, it was necessary to find a suitable traverse velocity by trial-and-error. With too slow a velocity, the jet tended to push the hard and strong fibers within the soft resin matrix, thus leaving some of the fibers uncut.
- The Kevlar/epoxy samples generally cut well. The cuts were for the most part smooth, but on the samples with the larger number of plies, the bottom fibers tended to pull into the cut, leaving a somewhat ragged appearance of the cut at the bottom plies.
- Most of the cut edges of the Kevlar/epoxy samples tended to be wetted by the jet, apparently due to the greater absorbancy of the Kevlar fibers compared to the other fibers in the test materials.
- The fiberglass/epoxy samples cut well with a fairly sharp, clean edge. The only anomaly was an apparent wetting of the epoxy resin for a short distance (approximately 1/32 inch away from the edge of the cut) as evidenced by a lightening of the color of the resin.

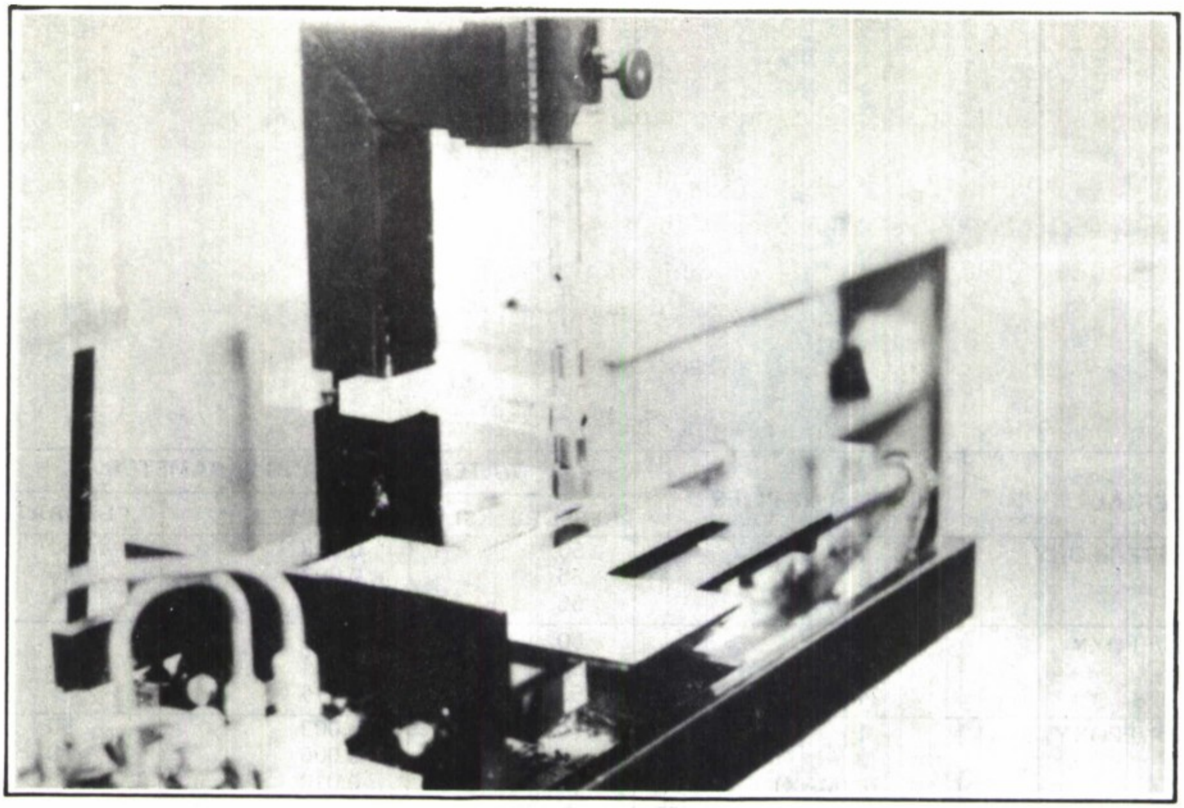

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Figure 4-18 Traverse Table with Sample in Place

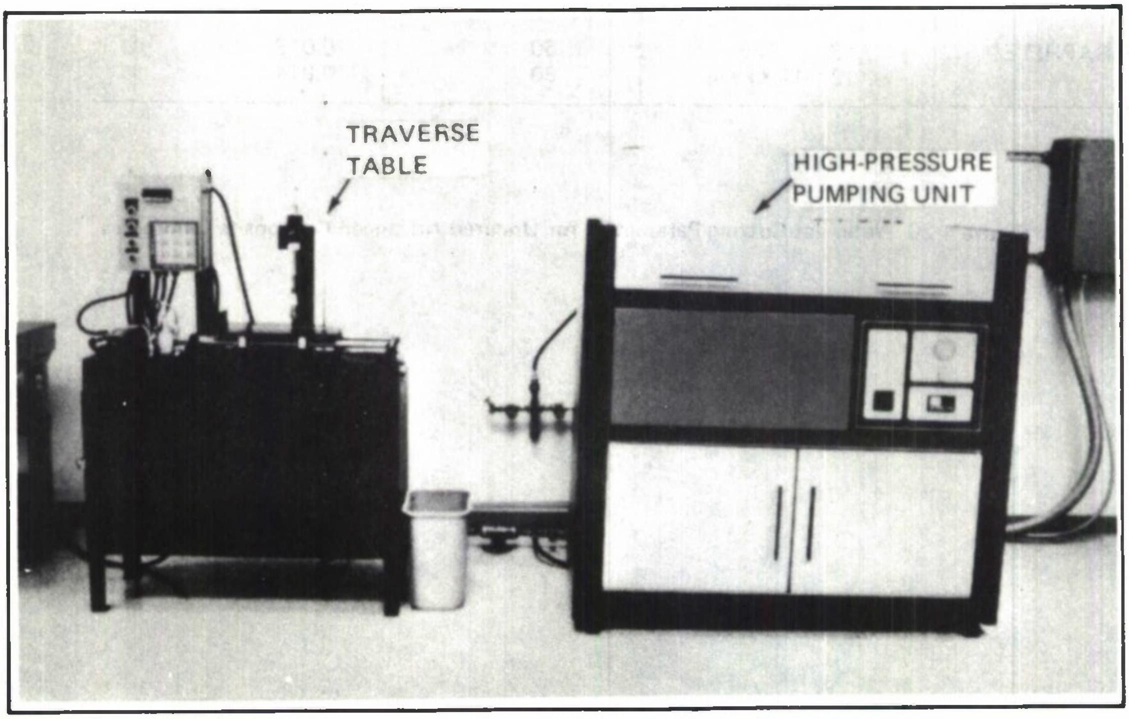

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Figure 4-19 General Arrangement of Water-Jet Cutting System

MATERIAL	NUMBER OF PLIES	WATER-JET CUTTING PARAMETER		
		PRESSURE, KSI	DIAMETER, IN.	FEEDRATE, IPS
GRAPHITE/EPOXY	1 3 30 (MAX)	50 55 55	0.003 0.003 0.010	50 40 1
BORON/EPOXY	1 3 24 (MAX)	60 55 55	0.014 0.014 0.014	10 15 8
KEVLAR/EPOXY	1 3 16 (MAX)	60 55 55	0.003 0.006 0.010	50 50 0.5
FIBERGLASS/EPOXY	1 3 12 (MAX)	60 55 55	0.006 0.010 0.010	50 10 0.5
HYBRID BORON-GRAPHITE/ EPOXY	3 12 (MAX)	60 60	0.012 0.014	8 8

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Figure 4-20 Water-Jet Cutting Parameters for Uncured Advanced Composite Laminates

4.2.2 Laser Cutting of Uncured Composites

A 250-watt, 10.6-micron-wavelength (far-infrared, not visible), continuous-wave, carbon dioxide laser manufactured by Coherent Radiation Laboratory (Model 41) was used for all cutting tests. The laser is mounted on a movable gantry (Figure 4-21) which is part of the production-oriented Integrated Laminating Center (ILC) being evaluated under Air Force Contract No. F33615-76-R-5389. A second degree of freedom has been achieved by mounting a movable optical system on the carriage assembly as shown in Figure 4-22. Cuts were made on specimens mounted to the vacuum table of the ILC using a 2.5-inch focal-length lens, 8-psi nitrogen gas assist, 0.060-inch nozzle gap and a 0.031-inch-diameter nozzle.

Laser cutting tests were performed on the four baseline materials and on Hercules 3004-AS graphite/polysulfone prepreg. The purpose of these tests was to establish parameters such as feed rate, nozzle size and style, and assist-gas pressure for a 250-watt, carbon dioxide-laser, production cutting tool, and the relationship of these parameters to cut quality (minimum fiber fraying, matrix retreat and matrix damage). Of the materials studied, graphite/epoxy and Kevlar/epoxy prepreg were laser-cut most readily while still providing desirable cut quality. Results are summarized in Figure 4-23 and discussed below.

4.2.2.1 Boron/Epoxy - All cuts were made on three-inch-wide tape laid up on polyethylene-coated paper (a production technique currently under consideration at Grumman). The paper alone consumes so little (if any at all) of the laser energy that it can be disregarded as having an influence on cutting parameters. The maximum attainable, effective cutting feed rate was 270 ipm. A broad range of feed rates (from 30 to 300 ipm) was tried. In general, the faster feed rates gave the best results. As feed rate decreases, the resin matrix is subjected to greater heat damage and retreat from the cut edge. The throat diameter of the assist-gas nozzle was found to be an insignificant factor in these tests. The shape and size of the assist-gas stream did not influence the cut quality of this material. The main requirement of the assist-gas nozzle in these tests is to assure blanketing of the area being cut with an inert gas. Nozzles having inside diameters of 0.026 and 0.032 inch were evaluated; no discernable difference in cutting ability or quality was detected. The 0.032-inch-diameter nozzle would be recommended only because it would be less critical with regard to maintaining concentricity with the laser beam. The lowest assist-gas

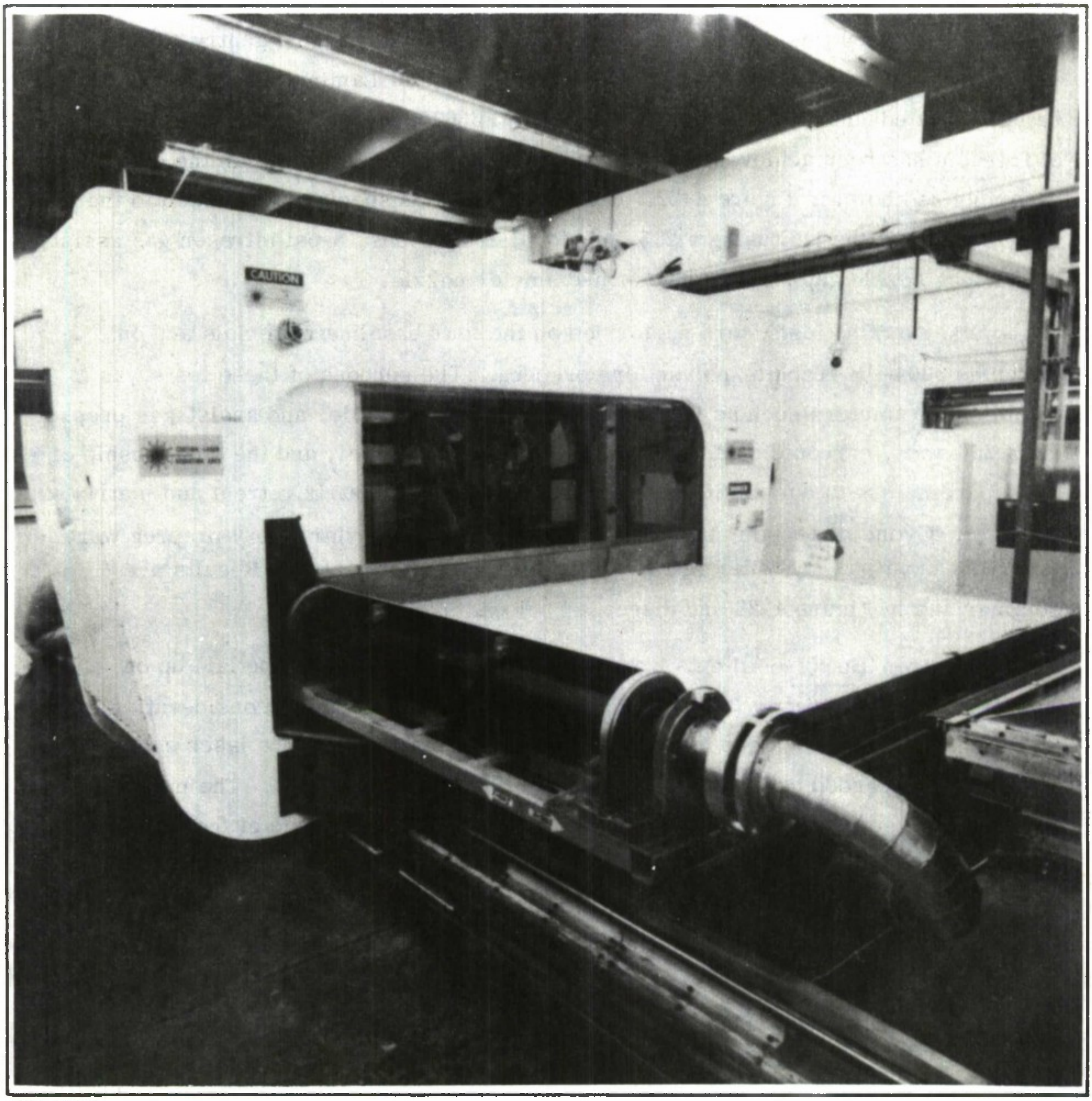

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Figure 4-21 Laser Trimming Station of Integrated Laminating Center

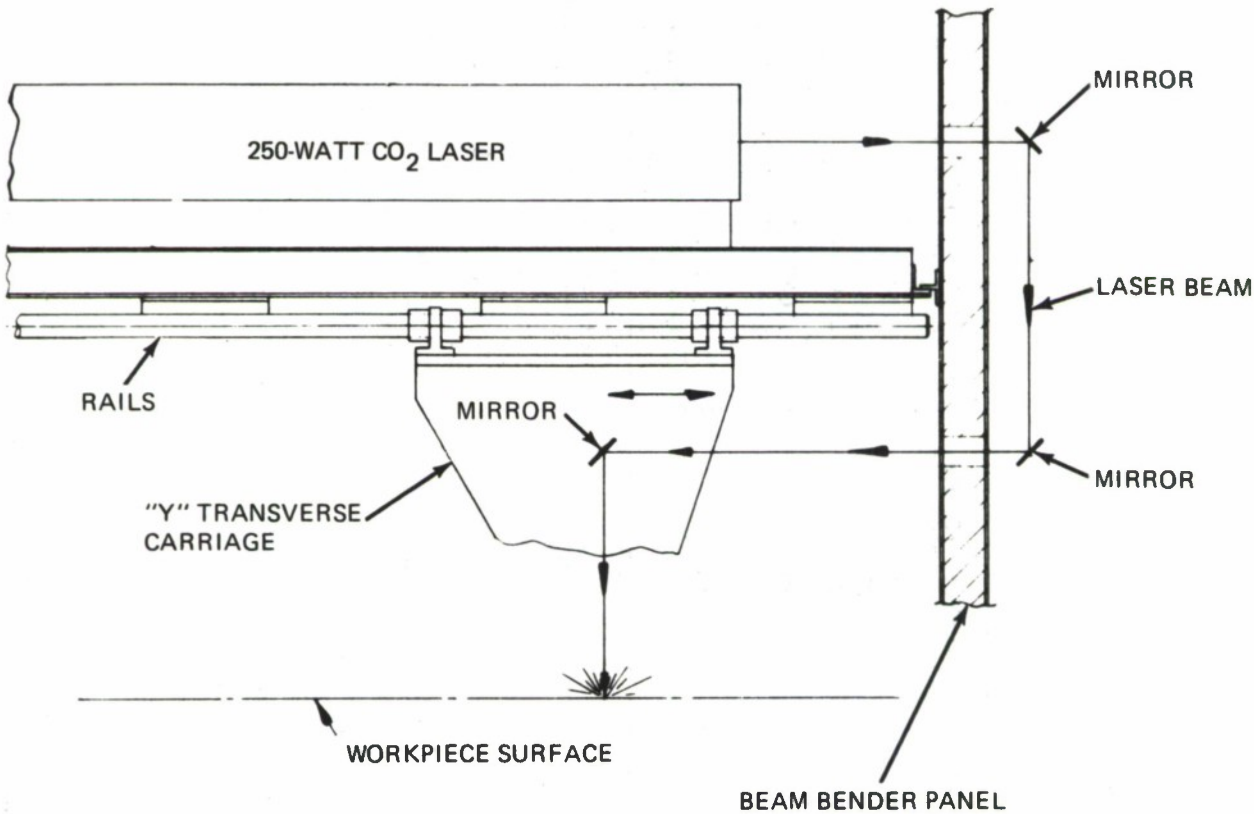

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Figure 4-22 Schematic Representation of Laser Cutting System

MATERIAL	NUMBER OF PLIES	FEEDRATE, IPM	REMARKS
KEVLAR/EPOXY BROADGOODS	1	300	CLEAN CUT
	2	300	CLEAN CUT
	3	300	CLEAN CUT
	4	300	CLEAN CUT
	5	300	CLEAN CUT; SMOKY EDGES
	6	300	INCOMPLETE
	B	100	CLEAN CUT BUT CONTAMINATED WITH SMOKE
FIBERGLASS/EPOXY BROADGOODS	1	300	CLEAN CUT
	2	150	CLEAN CUT
	3	90	CLEAN CUT BUT EPOXY BEAD ALONG EDGE FORMING
	4	60	CLEAN CUT; MORE PRONOUNCED EDGE BEAD
GRAPHITE/EPOXY TAPE	1	300	CLEAN CUT
	2	150	CLEAN CUT
	3	90	CLEAN CUT BUT EDGE BEAD EXCESSIVE
BORON/EPOXY TAPE	1	270	CLEAN CUT
	2	120	CLEAN CUT
	3	60	CLEAN CUT WITH EXCESSIVE RESIN RETREAT IN TOP PLY (0.010 INCH)
	4	30	MARGINAL CUT WITH INCREASED RESIN RETREAT
GRAPHITE BROADGOODS POLYSULFONE	1	300	BEST QUALITY ACHIEVED WITH 5 PSIG NITROGEN ASSIST GAS PRESSURE
GRAPHITE/POLYSULFONE	1	270	0.03-IN. RESIN RETREAT (AVG.)

NOTE: LASER PARAMETERS INCLUDED: 2.5-INCH FOCAL LENGTH LENS, 8 PSI NITROGEN ASSIST GAS, 0.06-INCH NOZZLE GAP, AND 0.03–INCH NOZZLE ORIFICE DIAMETER.

2566-015W

Figure 4-23 Summary of 250-Watt Laser Cutting Tests on Uncured Composites

pressure that is sufficient to eliminate oxygen from the cutting (laser beam) area and still remove smoke should be used. Laser cuts were made at pressures between 2 and 40 psi. Pressures above 10 psi appear to have a cooling effect which slows the cutting rate. A pressure of 5 psi was selected as the most suitable value. Boron/epoxy laminates up to four plies thick were also effectively laser-cut at a feed rate of 60 ipm. However, a significant amount of resin retreat (0.016 inch) occurred at this relatively slow feed rate. The best-quality cuts occurred in two-ply, boron/epoxy laminates cut at a feed rate of 120 ipm.

4.2.2.2 Graphite/Epoxy - All laser cuts were made with the graphite tape laid up on polyethylene-coated paper. Feed rates between 30 and 300 ipm were used. Cut quality was maintained at feed rates above 180 ipm (based on visual examination). Below this rate, matrix retreat led to fraying of the graphite fibers, probably by the assist-gas flow. The most effective cutting feed rate was found to be 300 ipm. Nozzles having an external conical shape, inside diameters of 0.025 and 0.32 inch, and an external flat nose with 0.032-inch inside diameter were tested. No difference in performance could be attributed to changes in inside diameter. Because the nozzle with the flat nose induced fiber fraying at the cut edge, its use is not recommended. The nozzle having the external conical shape and an inside diameter of 0.032 inch is recommended for use. Excessive assist-gas pressure (hence, velocity) is directly related to the degree of fiber fraying along the laser-cut edge. Several pressures were studied. As expected, the minimum pressure sufficient to blanket the cut area provided the best cut quality. An assist-gas pressure of 3-5 psi (gage) is recommended. Although graphite/epoxy tape laminates up to three plies thick were successfully laser-cut, a bead of partially cured epoxy resin developed along the edge of the cut at a feed rate of 60 ipm.

4.2.2.3 Kevlar/Epoxy - Kevlar/epoxy laminates were easily cut. Best-quality cuts were obtained in single-ply laminates at a feed rate of 300 ipm. The polyethylene film backup material did not interfere with the laser cutting operation. Laminates more than five plies thick had smoke contamination along the cut edges, probably due to the presence of air trapped between the plies. Five-ply laminates were cut at a feed rate of 300 ipm with good results.

4.2.2.4 Fiberglass/Epoxy - Laser cutting of uncured fiberglass/epoxy laminates can be accomplished at 300 ipm for single-ply thicknesses and for thicknesses up to three plies at a feed rate of 90 ipm. Higher feed rates reduced cut quality, apparently because of an inability to vaporize the resin quickly enough.

4.2.2.5 Woven Graphite Broadgoods - Woven graphite cloth was readily cut at a feed rate of 300 ipm. To improve cut quality, the nitrogen assist gas pressure was reduced to below 5 psi (gage). Slight fraying of loose fibers could not be eliminated even at these low assist-gas pressures. There was no evidence of heat damage to the fibers.

4.2.2.6 Graphite/Polysulfone - Graphite/polysulfone with its thermoplastic matrix exhibited the greatest matrix damage. As revealed by magnified visual examination, as much as 0.025 to 0.036 inch of the matrix material appears to have been removed. However, cutting rates up to 270 ipm were easily obtained.

4.2.3 Steel-Rule-Die Blanking

Tests to determine the feasibility of using steel-rule dies to blank uncured graphite/epoxy, boron/epoxy, Kevlar/epoxy and fiberglass/epoxy laminates were conducted at the Arvey Corporation. These tests were conducted on a 300-ton Sheridan press having a 30 x 40-inch platen area. The steel-rule die was positioned above a flat mild-steel plate to permit blanking on the down-stroke. Each die consisted of 0.118-inch-thick, one-side beveled, hardened steel strap imbedded in a wooden base with a cork stripper plate. This cutting edge configuration was found to give the highest quality compared to other standard configurations.

Single-ply laminates were positioned to permit cuts to be made in various directions relative to the fiber direction, as well as contoured cuts and 0.250-inch-diameter holes (Figure 4-24). With the exception of Kevlar/epoxy prepreg, the other composite materials cut cleanly and easily, requiring only minor die-position and pressure changes. Kevlar/epoxy required more buildup with paper and metal to get additional pressure and a better impression, than the other materials to achieve a clean separation of the blanked configuration.

Multi-ply cutting tests were also conducted with circular and triangular shapes to determine the effects of ply orientation (if any) and maximum number of plies. All materials, except Kevlar/epoxy prepreg, cut cleanly and easily as summarized in

Figure 4-25. The criterion used for selecting maximum number of plies was squareness of the cut. As the number of plies increased, edge squareness decreased. Tests showed Kevlar/epoxy to require significantly higher pressures. The fibers were also difficult to sever, thus restricting the maximum number of plies which could be cut.

In general, die life is not a major problem in the aircraft industry because of the relatively small quantities produced (compared to the appliance or automotive industries, for example). If a die does require reconditioning, only a minor expenditure is involved.

4.2.4 Recipro-Cutting

The Gerber Garment Technology System 90 (Figure 4-26) and the Gerber Scientific Instrument Company System 75 (purchased by Hamilton Standard) recipro-cutting machines were evaluated for uncured composites. Both units are similar in that they incorporate high-speed, reciprocating knives that are driven through the material to be cut by a mini-computer-controlled, X-Y-Z-C positioning system.

System 90 differs from System 75, however, in that the cutting knife penetrates through the material into closely packed plastic bristles that constitute the surface of the cutting table. This surface is non-degradable and does not require periodic refurbishment. The System 90 can cut desired patterns in a continuous line at high speed. Curves, sharp corners and notches can also be cut without lifting the knife from the material. The knife can be lifted, as required, to start new cutting lines, to pass over sections without cutting, or to cut holes of any diameter.

In System 75, the cutting knife ranges in width from 0.050 inch for the diamond cutter up to 0.175 inch for the carbide cutter (Reference 3). System 90 utilizes a 0.250-inch-wide blade. System 75 cuts in one mode (chopping) while System 90 cuts either by chopping or slicing (Figure 4-27). In the chopping mode, the knife rises above and plunges through the material onto the table. In the slicing mode, the knife remains buried in the material after the first stroke (each stroke is 3/4 inch) and is always at least 1/8 inch below the material being cut. Computer-controlled rotation of the knife about the C-axis keeps the blade properly positioned at all times.

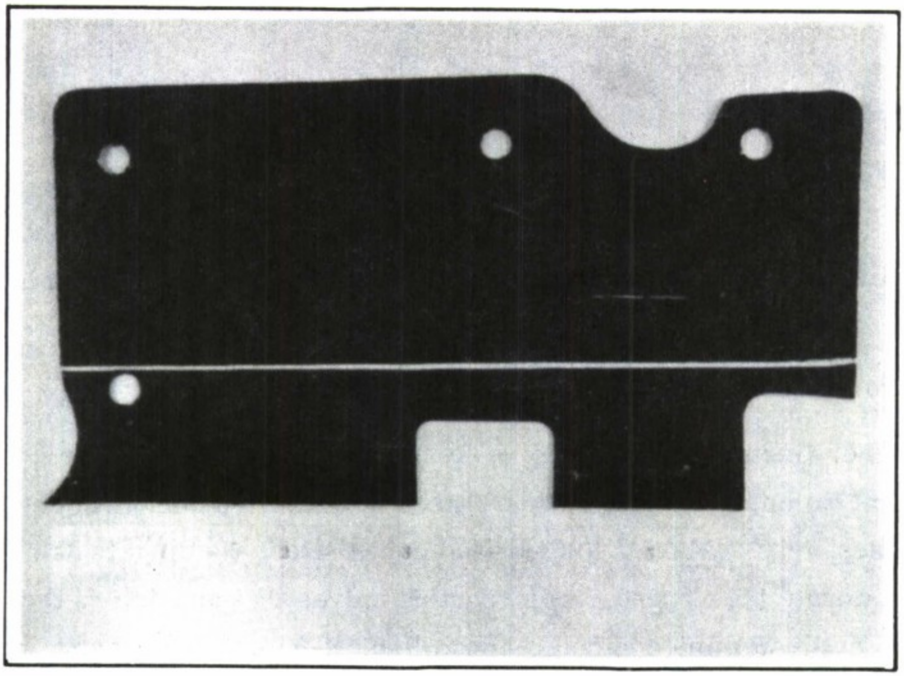

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Figure 4-24 Uncured Graphite/Epoxy Configuration Blanked by Steel-Rule Die

MATERIAL	MAXIMUM NUMBER OF PLIES	CONFIGURATIONS	CUT QUALITY
GRAPHITE/ EPOXY	18	CIRCLES: 2-1/2-INCH DIAMETER WITH 7/16-INCH DIAMETER HOLES	EXCELLENT
	18	TRIANGLES: 3-INCH WITH 11/16-INCH DIAMETER HOLES	EXCELLENT
BORON/EPOXY	18	TRIANGLES: 3-INCH	EXCELLENT
	18	TRIANGLES: 3-INCH WITH 11/16-INCH DIAMETER HOLES	EXCELLENT
KEVLAR/ EPOXY	12	TRIANGLES: 3-INCH	GOOD
FIBERGLASS/ EPOXY	27	TRIANGLES: 3-INCH	EXCELLENT

NOTE: ALL BLANKING WAS DONE WITH TOP AND BOTTOM POLYETHYLENE COVER SHEETS.

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Figure 4-25 Summary of Steel-Rule-Die Blanking of Uncured Laminates

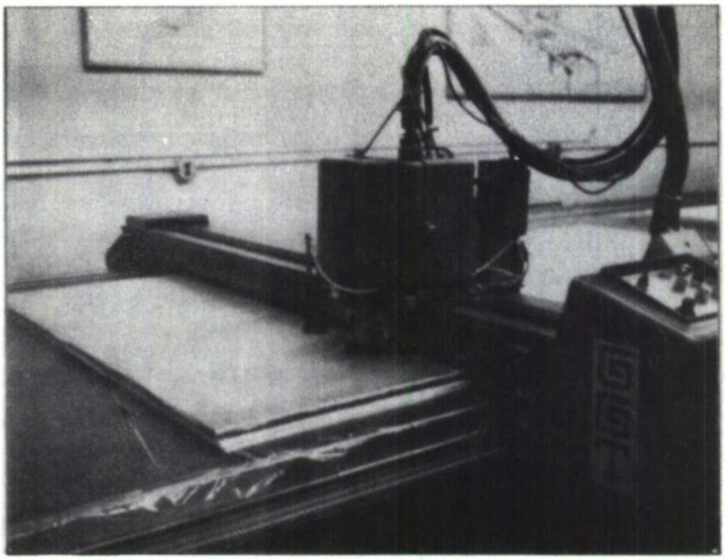

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Figure 4-26 Gerber System 90 Recipro-Cutting System

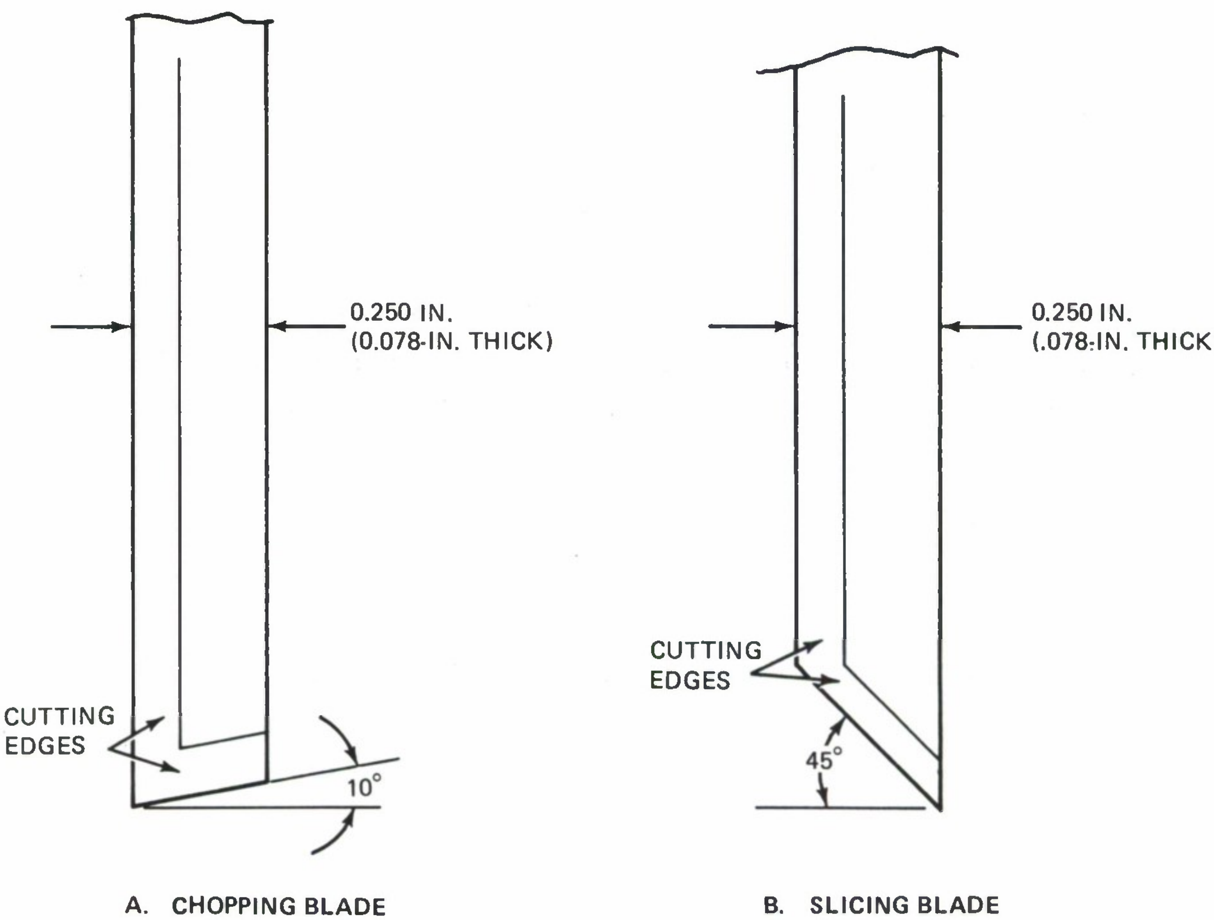

Figure 4-27 Gerber System 90 Cutting Blade Types

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System 90 has the following advantages over System 75:

- Feed rate is 1200 inches per minute -- almost twice that of System 75. (Both systems use the same number of strokes per minute - 6000).
- Knife depth is not critical, since the knife penetrates through the material being cut into the plastic bristle table.
- Knife stroke is 7/8 inch compared to 3/16 inch for System 75.
- Fine, knife-depth adjustments are not required.

Cutting test results for both System 90 and System 75 are summarized in Figure 4-28. Tests conducted at Gerber Garment Technology Inc., East Hartford, Connecticut, indicate that System 90 can cut a greater number of fiberglass/epoxy and graphite/epoxy plies at twice the feed rate. Visual inspection showed that the quality of the edges of laminates cut by both systems is about equivalent.

4.3 PREPLACEMENT OF HOLES IN UNCURED LAMINATES

4.3.1 General

The purpose of this task was to determine the feasibility of various methods of preplacing holes in uncured advanced composites. Initially, several approaches for producing 1/8-, 3/16-, 1/4- and 1/2-inch-diameter holes were screened. These hole diameters represent potential areas of application based on experience with the B-1 horizontal stabilizer.

Hole preplacement methods considered included water-jet, laser, reciprocating and steel-rule die cutting. An approach that was not studied involved parting the fibers or forming the holes. This particular study was previously reported by the Naval Air Development Center (Reference 4).

4.3.2 Computer-Directed Cutting Systems

Producing holes smaller than one inch in diameter is a time-consuming task for such computer-directed processes as water-jet, laser and reciprocating cutting. For example, a reciprocating cutting system required 40 seconds to cut a 1.0-inch-diameter hole in a four-ply graphite/epoxy laminate. The water-jet and laser cutting systems can quickly make holes having the diameters of the water-jet (0.010-0.012 inch) and laser (0.005 inch), respectively. These small-diameter holes are not practical for reducing the number of drilling operations in cured composite parts.

DATA SUMMARY											
GERBER CUTTING SYSTEM 90 (WORK DONE AT GERBER GARMENT TECHNOLOGY, INC.)											
MATL CODE/ RUN	MATL	PLIES	COMPOSITE MATL ORIENTATION (DEG)	COVER SHEET NOTE 1	CUT DIREC-TION (DEG)	CUTTER MATL	CUTTER MODE	CUTTER WIDTH	FEED RATE, IN./ MIN	CUTTER STROKES/ MIN	REMARKS
G-1	GR/EP	1	0	NONE	90	CARBIDE	CHOPPING	1/4	600	5000	GOOD CUT
G-2	GR/EP	1	0	NONE	10 SKEW	CARBIDE	CHOPPING	1/4	600	5000	SOME FIBERS NOT CUT (2)
G-3	GR/EP	5	0,0,45,0,0	PAPER	0	CARBIDE	CHOPPING	1/4	600	5000	FUZZY
G-4	GR/EP	5	0,0,45,0,0	PAPER	0	HSS	SLICING	1/4	600	5000	GOOD CUT
G-5	GR/EP	8	0,0,45,90,90,45, 0,0	PAPER	0	HSS	SLICING	1/4	600	5000	GOOD CUT
G-6	GR/EP	8	0,0,45,00,00,45, 0,0	PAPER	0	HSS	SLICING	1/4	900	6000	GOOD CUT, SAME AS RUN 5
G-7	GR/EP	13	0,0,45,90,90,45, 0,0,0,0,45,0,0	PAPER	0	HSS	SLICING	1/4	600	5500	ACCEPTABLE, A LITTLE FUZZY
G-8	GR/EP	21	0,0,45,90,00,45, 0,0,0,0,45,90,90 45,0,0,0,0,45,0,0	PAPER	0	HSS	SLICING	1/4	600	5500	FUZZY
F-1	FIBER/ GLASS/EP	1	0	NONE	0	CARBIDE	CHOPPING	1/4	600	5300	BEST, LITTLE FUZZY ON EXIT
F-2	FIBER/ GLASS/EP	1	0	NONE	0	CARBIDE	CHOPPING	1/4	300	4200	GOOD CUT
F-3	FIBER/ GLASS/EP	1	0	NONE	0	CARBIDE	CHOPPING	1/4	900	6000	GOOD CUT
F-4	FIBER/ GLASS/EP	1	0	NONE	0	HSS	SLICING	1/4	600	5300	NOT GOOD, WIDE CUT
F-5	FIBER/ GLASS/EP	4	0	NONE	0	CARBIDE	CHOPPING	1/4	600	5300	NOT GOOD, FUZZY
F-6	FIBER/ GLASS/EP	4	0	NONE	0	CARBIDE	CHOPPING	1/4	600	6000	NOT GOOD, WORSE
F-7	FIBER/ GLASS/EP	4	0	NONE	0	CARBIDE	CHOPPING	1/4	600	3500	BETTER
F-8	FIBER/ GLASS/EP	4	0	NONE	0	CARBIDE	CHOPPING	1/4	600	3100	BEST CUT, LITTLE FUZZY ON EXIT
F-9	FIBER/ GLASS/EP	6	0,0,90,00,0,0	NONE	0	CARBIDE	CHOPPING	1/4	450	3700	NOT GOOD
F-10	FIBER/ GLASS/EP	8	0,0,00,00,0,0	NONE	0	CARBIDE	CHOPPING	1/4	450	4500	WORSE
F-11	FIBER/ GLASS/EP	8	0,0,0,90,90,0,0,0	NONE	0	CARBIDE	CHOPPING	1/4	450	4400	NOT GOOD, FUZZY
X-1	KEVLAR/ EPOXY	1	0	NONE	0	CARBIDE	CHOPPING	1/4	600	3700	NOT GOOD
X-2	KEVLAR/ EPOXY	1	0	PAPER	0	CARBIDE	CHOPPING	1/4	600	3700	BEST CUT
X-3	KEVLAR/ EPOXY	4	0	PAPER	0	CARBIDE	CHOPPING	1/4	600	4500	BEST, SOME FUZZ ON EXIT SIDE
X-4	KEVLAR/ EPOXY	4	0	NONE	0	CARBIDE	CHOPPING	1/4	600	4500	NOT GOOD
X-5	KEVLAR/ EPOXY	8	0,0,90,90,0,0	PAPER	0	CARBIDE	CHOPPING	1/4	600	5000	A LITTLE FUZZY
X-6	KEVLAR/ EPOXY	8	0,0,90,90,0,0	NONE	0	CARBIDE	CHOPPING	1/4	600	5000	A LITTLE FUZZY

SELECTED DATA												
GERBER CUTTING SYSTEM 775 (WORK DONE AT HAMILTON STANDARD)												
MATL CODE/ RUN	MATL	PLIES	COMPOSITE MATL ORIENTATION (DEG)	COVER SHEET	CUT DIREC-TION (DEG)	CUTTER MATL	CUTTER TYPE, DEG	CUTTER WIDTH	CUTTER DEPTH	FEED RATE	REMARKS
G-7	GR/EP	1	0	POLYETHYLENE	0	CARBIDE	15	0.125	0.031	300	BEST CUT
G-13	GR/EP	4	0,90,90,0	PAPER	0	CARBIDE	15	0.125	0.053	300	GOOD CUT
G-18	GR/EP	8	0,0,45,90,90,45,0,0	PAPER TOP AND BOTTOM	0	CARBIDE	15	0.125	0.091	300	BEST CUT
F-3	FIBER/ GLASS/EP	1	0	PAPER	0	CARBIDE	25	0.125	0.035	600	GOOD CUT
F-5	FIBER/ GLASS/EP	4	0	PAPER	0	CARBIDE	25	0.125	0.076	600	GOOD CUT
K-3	KEV/EP	1	0	PAPER	0	CARBIDE	25	0.125	0.045	600	BEST CUT
K-7	KEV/EP	4	0	PAPER	0	CARBIDE	25	0.125	0.085	600	A LITTLE FUZZY

(1) ALL CUTS MADE WITH POLYETHELENE SHEET ON BOTTOM, EXCEPT AS NOTED
(2) PREVIOUS TESTS BY GERBER PRODUCED GOOD CUTS WITH SLICING MODE.

2566-016W

Figure 4-28 Comparison of Recipro-Cutting Tests of Uncured Composites

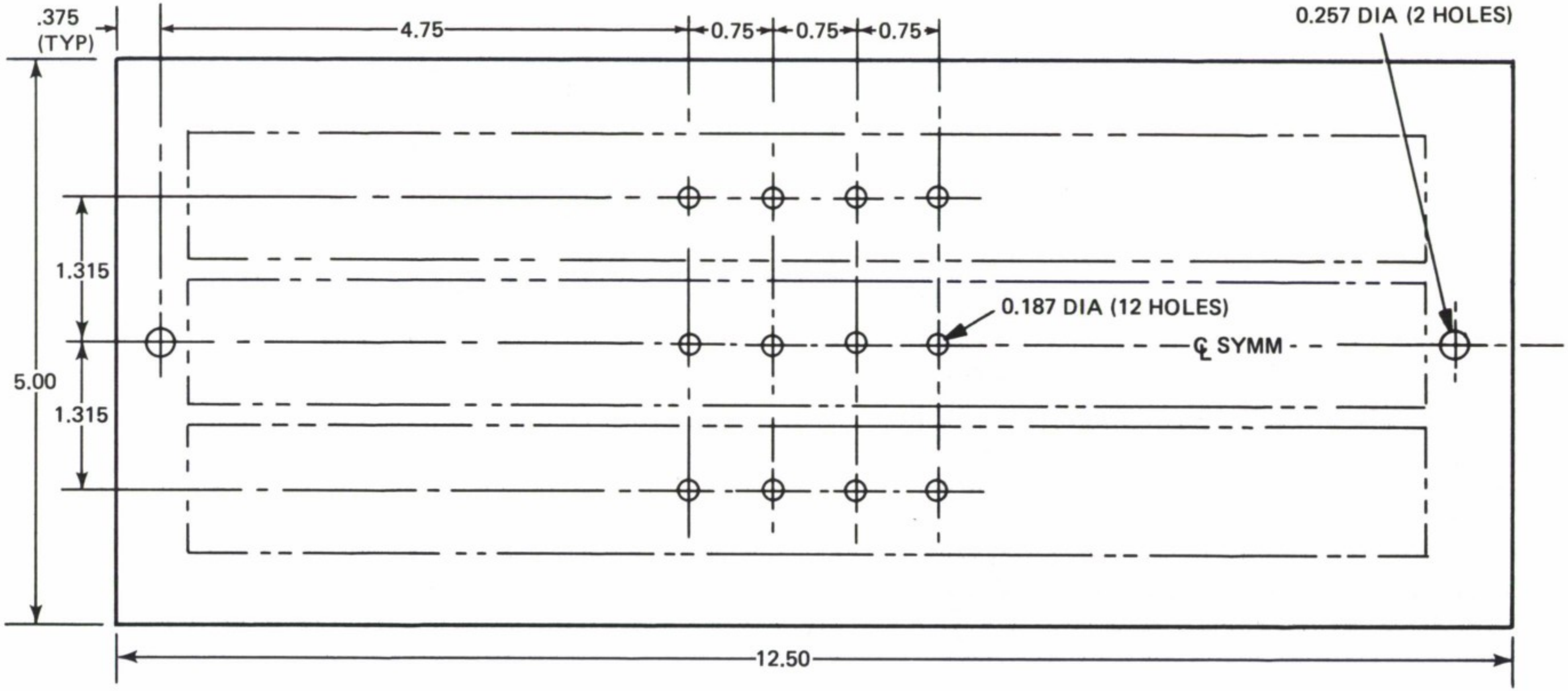
In general, the time required to generate a 0.187-inch diameter circular path by a computer-directed system would be approximately 1.5 secs. Against new drilling parameters developed with this program, cost effectiveness could not be justified for graphite/epoxy structure. In addition, these new cutting techniques are not adaptable to the more-expensive-to-drill boron/epoxy composite in stacked thicknesses.

4.3.3 Blanking

Based on preliminary tests conducted with uncured graphite/epoxy and boron/epoxy hollow laminates, two types of piercing dies were fabricated -- a steel-rule die with hollow punches (No. RDM 447-1274-11) and a ground flat-stock die with solid punches (No. RDM 447-1274-13). The steel-rule die was made for use with the relatively soft graphite/epoxy and Kevlar/epoxy laminates, while the ground flat-stock die was made for use with the relatively hard boron/epoxy laminates. The 0.187-inch-diameter and 0.257-inch-diameter hole patterns shown in Figure 4-29 were pierced in 9-ply graphite/epoxy laminates and 6-ply hybrid Kevlar/epoxy-plus-graphite/epoxy laminates. A 6-ply boron/epoxy laminate was pierced with the ground flat-stock die to give the same hole pattern. The pierced blanks were stacked using 0.250-inch-diameter pins in the 0.257-inch-diameter holes at each end of the blanks for the number of plies and orientations shown in Figure 4-29. The quality of the holes in all stacks was excellent.

The laminate stacks were prepared for curing as shown in Figure 4-29. The holes in panels having preplaced holes with no restraints filled up with resin during the curing cycle. Alternate approaches using pins and washers in place of rivets in the panels to preplace the holes caused dimpling at the hole sites (Figure 4-30). The length of restraints used allowed for compaction of the laminate during curing. The boron/epoxy panels (Code No. B-2-1) cured only with pins, however, maintained thickness in the hole areas. Using pins alone was the best of the hole-restraint methods evaluated. Excess resin collected around the rivet heads during curing of the high-temperature boron/epoxy panel (Code No. B2-2).

All stacks were post-cured without the hole restraints and ultrasonically checked for defects before testing. The static tension matrix is shown in Figure 4-31. The ultrasonic scans for the post-cured panels were satisfactory except for the Kevlar/epoxy hybrid panels (No's. K-2-1, K-2-2 and K-3-2) and boron/epoxy panel No. B-1-1 which had some anomalies in the hole sites. This was confirmed by subsequent Fokker bond tests that indicated possible delaminated areas.



DASH NO.	QUANT	TOT THK	MATERIAL	PLY	ORIENTATION
–1	3	.189	GRAPHITE/EPOXY	36	45,135,90,90,45,135,0,0,45 135,90,90,45,135,45,135,0,0,℄
–3	3	.136	BORON/EPOXY	26	45,135,90,45,135,0,0,0 0,45,135,0,0,℄
–5	3	.126	GR/EP + KEVLAR / EP	19	45,135,0,0,45,135,90,45 135,0,135,45,90,135,45,0,0,135,45

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Figure 4-29 Pre-Placed Hole Test Coupons – Uncured Composites

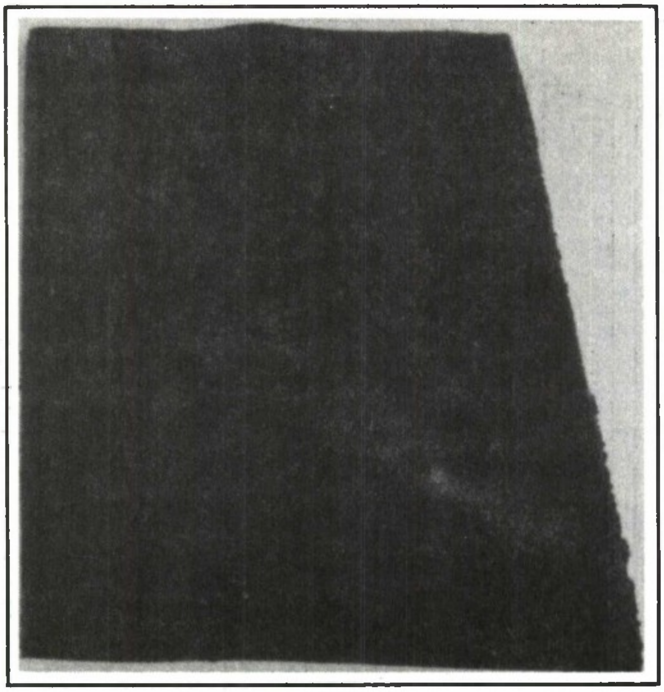

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Figure 4-30 Cured Graphite/Epoxy Panel (No. G-2-1) with Dimpling Caused by Rivets Used as Hole Restraints

MATERIAL	THICKNESS, INCH	TYPE OF HOLE	73°F CODE	NO.	300°F CODE	NO.
GRAPHITE/EPOXY	3/16	PUNCHED HOLES AND REAMED	G-1-1	3	G-1-2	3
		PUNCHED HOLES CURED WITH RIVETS	G-2-2	3	G-2-2	3
		DRILLED HOLES (CONTROL)	G-3-1	3	G-3-2	3
BORON/EPOXY	1/8	PUNCHED HOLES AND REAMED	B-1-1	3	B-1-2	3
		PUNCHED HOLES CURED WITH PINS FOR 73°F AND RIVETS FOR 300°F	B-2-1	3	B-2-2	3
		DRILLED HOLES (CONTROL)	B-3-1	3	B-3-2	3
KEVLAR/EPOXY PLUS GRAPHITE/EPOXY	1/8	PUNCHED HOLES AND REAMED	K-1-1	3	K-1-2	3
		PUNCHED HOLES CURED WITH PINS AND WASHERS	K-2-1	3	K-2-2	3
		DRILLED HOLES (CONTROL)	K-3-1	3	K-3-2	3

2199-103B

Figure 4-31 Static Tension Test Matrix For Preplacement Of Holes

The test panels were checked after curing for hole position using a master template and for hole size. The 0.250-inch-diameter holes at each end of the panels were positioned within ±0.002-inch over the 11.75-inch distance. Some of the 0.1875-inch-diameter holes controlled by hole restraints during the cure cycle shrunk slightly during the post-cure cycle to a diameter of 0.1865-inch.

Punched holes in panels without restraints filled up with epoxy resin during curing; as a result, these panels were drilled and reamed to size. The carbide drills used to remove resin in boron/epoxy panels become dulled and scarred. The holes were then reamed with diamond-coated Flexolap reamers. The control panels were drilled and cut by the optimum method.

4.3.4 Tensile Testing

Results of the room temperature and 300°F static tensile tests on three types of materials are summarized in Figure 4-32. All specimens were tested to failure on a Wiedmam-Baldwin Mark 30B universal testing machine at a constant cross-head rate. The tensile specimens contained four in-line open holes (0.1875-in. nominal diameter). Six coupons for each material were tested, including drilled holes (control), punched holes reamed after curing, and punched holes cured with hole restraints. Specimens having indications of possible defects as revealed by ultrasonic NDT did not produce exceptional scatter in failure loads.

Except for boron/epoxy specimens having punched holes cured with restraints, the average net stress for the control specimens exceeded that for specimens with punched and reamed holes, and those with punched and restraint-cured holes. The average net stress of the boron/epoxy control specimens exceeded that for the specimens with punched and restraint-cured holes by five percent at room temperature; at 300°F, the average net stress for the control specimens was four percent less. These small differences in the average net stress values can be attributed to the easier control of the thickness of the boron/epoxy laminates. As a result, the lengths of the pins and rivets used were more precisely established with respect to the final compacted laminate thickness.

Predicted average net stress values at 73°F and 300°F are presented in Figure 4-32. Force values were obtained from Grumman-generated data. In most cases, the average net stress for punched holes cured with restraints in the three materials studied exceeded the predicted stress. Although the work reported represents only an initial evaluation, there is a trend that curing punched holes with restraints in boron/epoxy laminates is a viable method.

TYPE OF SPECIMEN	MATERIAL	NUMBER TESTED AT EACH TEMP	AVERAGE NET STRESS, PSI		PREDICTED AVERAGE NET STRESS, PSI	
			73°F	300°F	73°F	300°F
PUNCHED AND REAMED HOLES	GRAPHITE/EPOXY	3	41,737	44,626		
PUNCHED HOLES CURED WITH RESTRAINTS	(3501-5/AS1-5)	3	46,597	52,090		
DRILLED HOLES (CONTROLS)		3	54,862	59,341	44,850	44,850
PUNCHED AND REAMED HOLES	BORON/EPOXY	3	88,721	85,056		
PUNCHED HOLES CURED WITH RESTRAINTS	(5505/4)	3	90,945	93,000		
DRILLED HOLES (CONTROLS)		3	95,476	89,365	72,450	70,725
PUNCHED AND REAMED HOLES	KEVLAR/EPOXY (5143/285)	3	39,679	36,266		
PUNCHED HOLES CURED WITH RESTRAINTS	PLUS	3	36,568	32,955		
DRILLED HOLES (CONTROLS)	GRAPHITE/EPOXY 3501-5!/AS (26.3%)	3	45,078	41,814	31,940	30,045
RESULTS FROM NAVAL AIR DEVELOPMENT CENTER REPORT (REFERENCE 10)						
FORMED HOLE	GRAPHITE/EPOXY (3501-AS)	13	60,002			
DRILLED HOLE (CONTROL)		13	37,797			

2566-017W

Figure 4-32 Summary of Static Tensile Tests for Preplaced Holes

Preplacing holes by punching and reaming only is not considered desirable because the holes had to be drilled and reamed again after curing to remove excess resin and because the average net stress for these specimens fell below the predicted stress in some cases.

4.3.5 Parted Fibers (as reported in Reference 4)

This discussion is presented for comparative purposes only and does not represent a task performed under this contract. Holes in structural members introduce areas of high stress concentration. When laying up a composite laminate, it is possible to form the holes before cure, instead of cutting the fibers by drilling the holes after cure. The diverted fibers maintain their continuity and provide added strength in the highly stressed region around the hole (Figure 4-33). Accordingly, a laminate with formed holes would be stronger than a similar laminate with drilled holes. Compilation of data from industry and DOD programs showed that such an effort was conducted in the program, "A Comparison of the Status and Fatigue Strengths of Formed and Drilled Holes in Composite Laminates". During this program, tests were carried out on graphite/epoxy laminates to investigate the feasibility of this technique. An 18-ply (0°, ±45°, 0°, ±45,±45°) layup was chosen for the test specimens. Holes of 1/4 inch diameter were formed in the graphite/epoxy laminate by diverting the fibers and inserting steel pins to form the holes (Figure 4-34). The pins were removed after the cure cycle. There was an approximately 10% increase in laminate thickness in the immediate area around the formed holes. Tension, compression, shearout and bearing specimens were prepared and tested, together with similar samples having drilled holes.

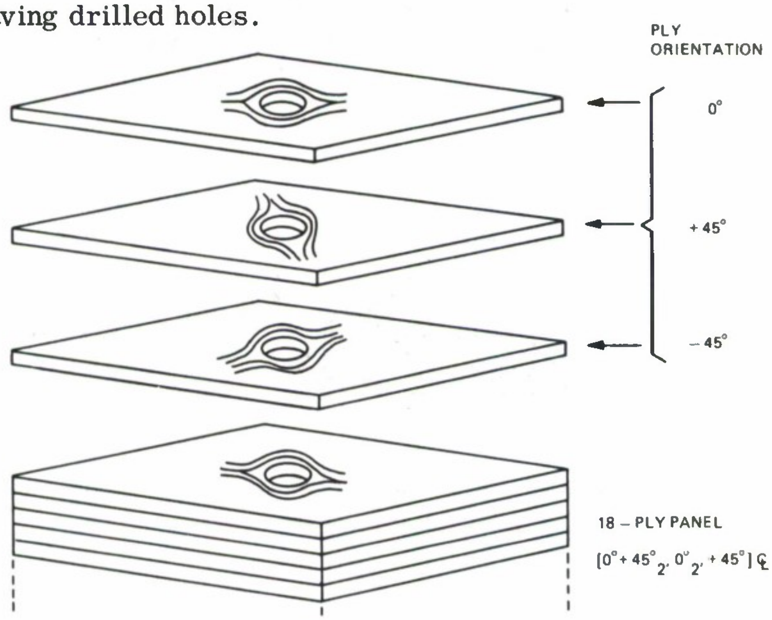

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Figure 4-33 Fiber Spreading to Form Hole

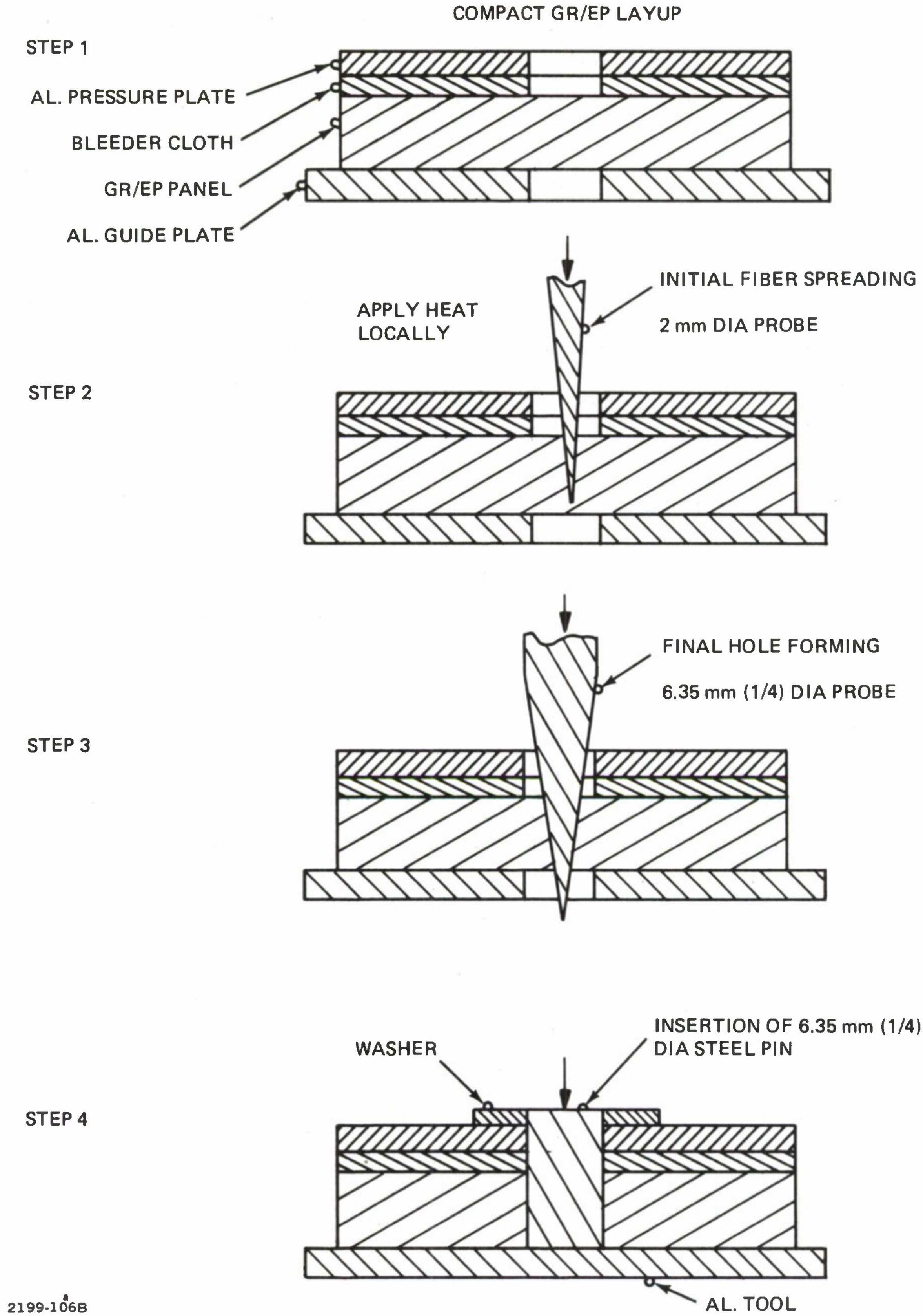


Figure 4-34 Fabrication Process

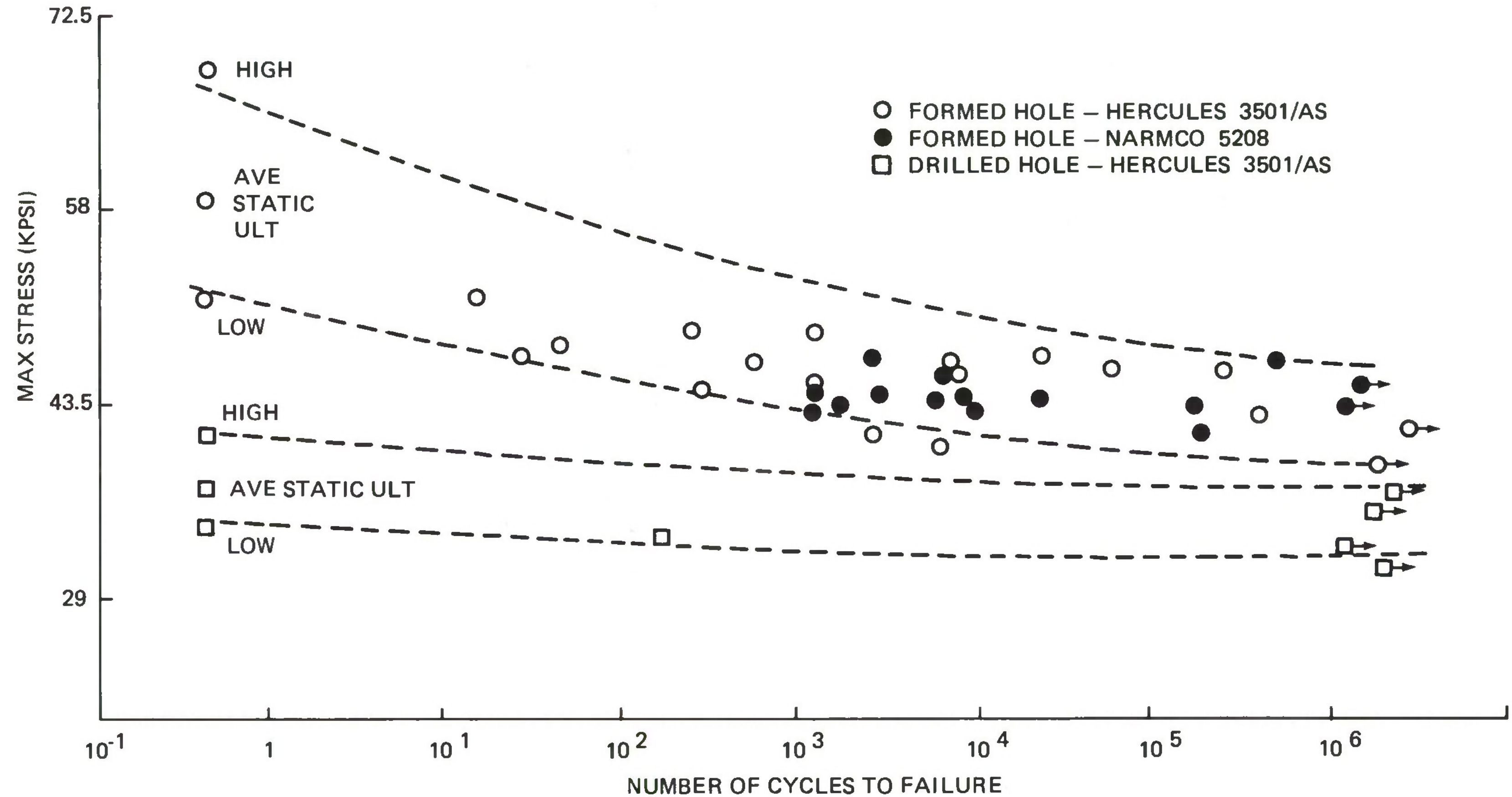
Open-hole tests on formed-hole specimens showed a 50% improvement in tensile strength (Figure 4-35) and a 26% improvement in compressive strength over drilled hole specimens. The shearout specimens of both types failed at essentially the same loads. The formed-hole bearing specimens experienced an initial yielding at approximately 50% of the ultimate bearing load, whereas the drilled hole specimens yielded at 75% of ultimate. However, the ultimate load in bearing for both types of specimen was about the same.

Open-hole fatigue tests were also conducted to compare fatigue characteristics (R=0 and R=1) of a graphite/epoxy laminate containing a formed hole to one containing a drilled hole. Test results showed excellent fatigue properties for the formed hole specimens and established that their added static strength capability could be fully utilized in structural component design (Figure 4-36)

TYPE SPECIMEN	NUMBER TESTED	AVG ULT LOAD, LB	AVG STRESS, PSI	NOMINAL STRESS CONC FAC, "K"
BASE (NO HOLE)	27	7,549	69,807	1.00
DRILLED HOLE	25	4,049	37,710	1.85
FORMED HOLE	24	6,360	56,507	1.19

2566-018W

Figure 4-35 Average Results for All Tension Tests



2566-171W

Figure 4-36 Open Hole Fatigue Tests for Formed Holes

4.4 CUTTING CURED COMPOSITES WITH NEW TECHNOLOGY METHODS

The two, principal new-technology approaches which are considered primary candidates for future production implementation are high-pressure water-jet cutting and laser cutting.

4.4.1 Water-Jet Cutting of Cured Composites

Water-jet cutting tests were performed by Flow Research, McCartney, and IIT Research Institute.

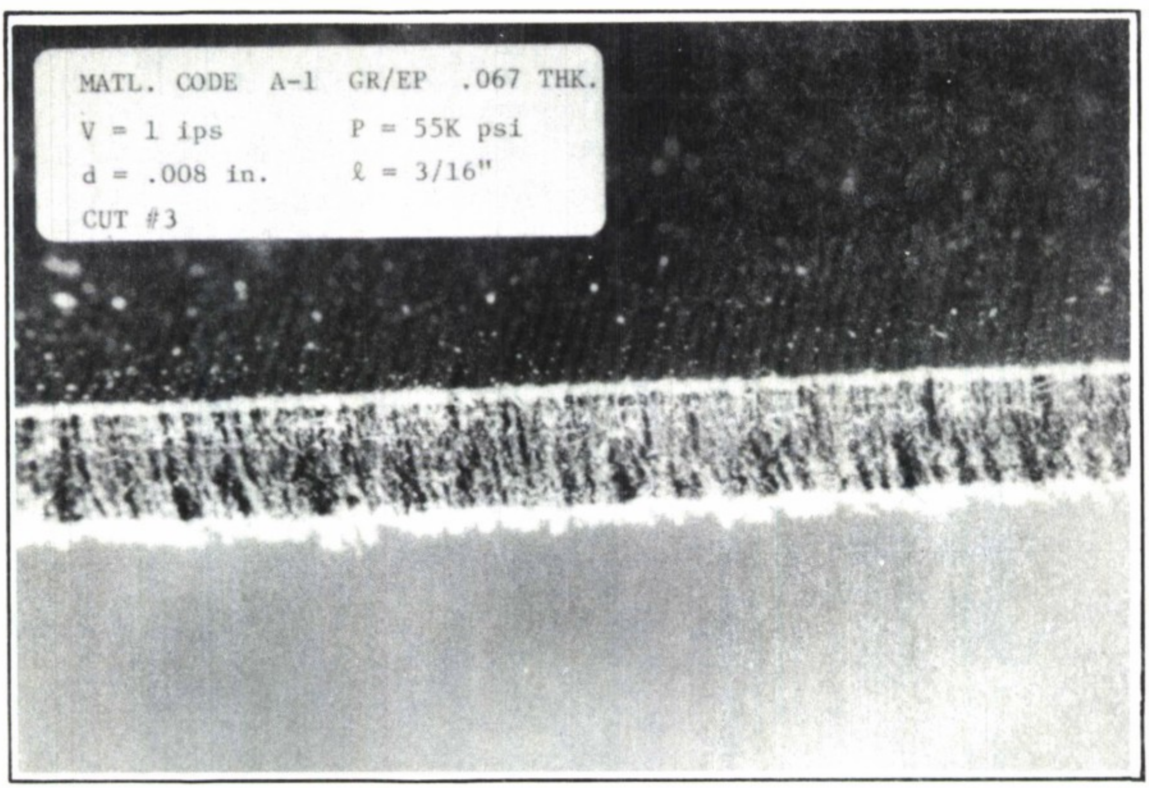
4.4.1.1 Flow Research Baseline Tests - The baseline cutting tests were conducted under subcontract by the Flow Research Company (Reference 2 and see equipment description in Section 4.2.1). It was found that water-jet cutting performance is affected by jet pressure (p), nozzle orifice diameter (d) and traverse speed (v) which, in turn, are governed by the type and thickness of the material to be cut. Nozzle standoff distance was held constant at about 1/8 inch. After a series of cutting tests was completed for each material, cut quality was subjectively rated on the basis of cut appearance and cutting parameters (p, d and v) used. If a group of cuts on a single material were about equal in appearance, the cut made with the lowest pressure and diameter, and largest velocity, was selected as best. In this way, pumping horsepower was minimized while cutting rate was maximized.

Cured samples were cut primarily in the zero-degree direction so that the cuts would be parallel to the direction of the reinforcing fibers. After completion of the zero-degree cuts and selection of the optimum parameters, a control cut was made in the 90-degree (transverse) direction. Very little difference, if any, was observed in the performance of the water jet or the quality of the cuts during the control tests on the advanced composite materials with the exception of the boron/epoxy samples.

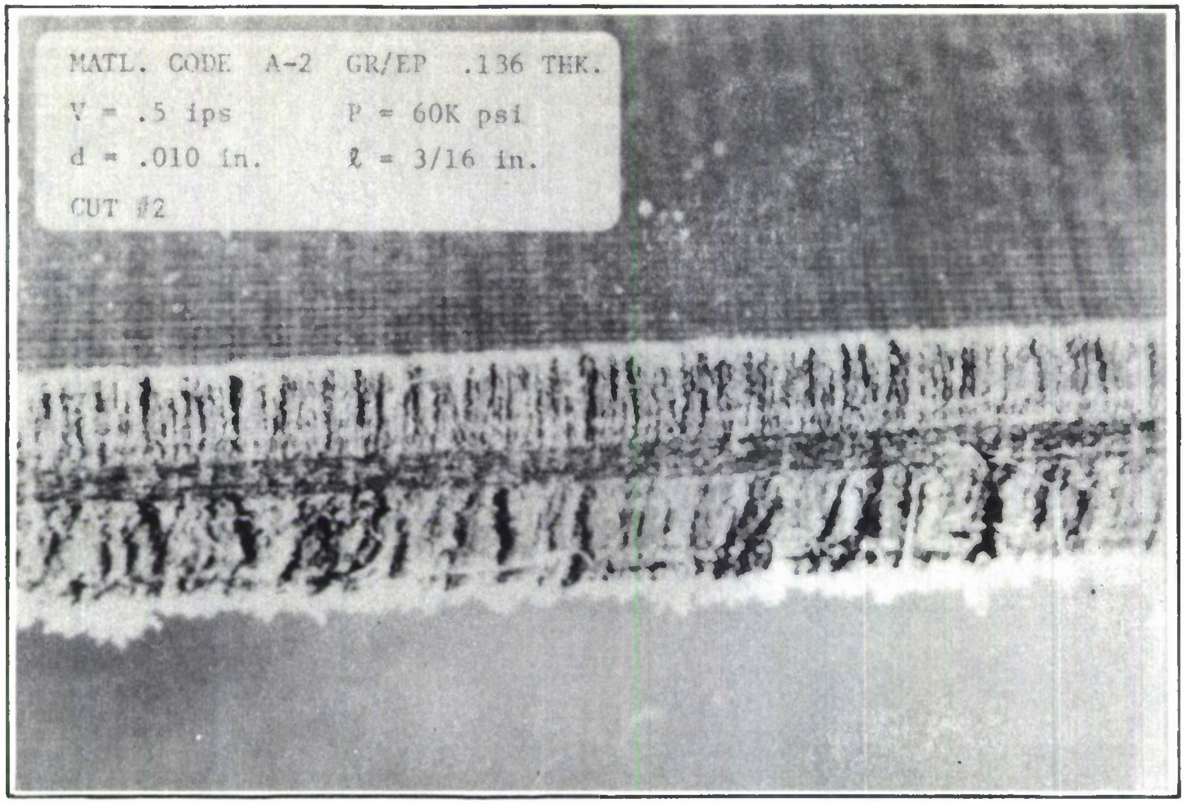
Water-jet cutting parameters for the best-cut, cured samples are summarized in Figure 4-37. The cut edges of each of the cured samples are shown in Figures 4-38 through 4-52. Each cut shown is the optimum or best cut for each material based on visual quality (see Section 7 for NDE results).

MATERIAL	THICKNESS, IN.	WATER-JET CUTTING PARAMETER		
		PRESSURE, KSI	DIAMETER, IN.	FEEDRATE, IPM
GRAPHITE/EPOXY	1/16 1/8 1/4	55 60 60	0.008 0.010 0.014	60 30 7
BORON/EPOXY	1/16 1/8	60 60	0.012 0.010	120 120
KEVLAR/EPOXY	1/16 1/8	55 55	0.006 0.010	120 30
FIBERGLASS/EPOXY	1/8	60	0.010	6
HYBRID BORON-GRAPHITE/ EPOXY	1/16 1/8 1/4	60 60 60	0.012 0.012 0.014	14 12 9
HYBRID GRAPHITE-KEVLAR/ EPOXY	1/16 1/4	60 60	0.010 0.014	15 5
HYBRID GRAPHITE-FIBERGLASS/ EPOXY	1/16 1/4	55 55	0.012 0.012	9 9

2199-109B **Figure 4-37 Water-Jet Cutting Parameters for Cured Advanced Composite Laminates**

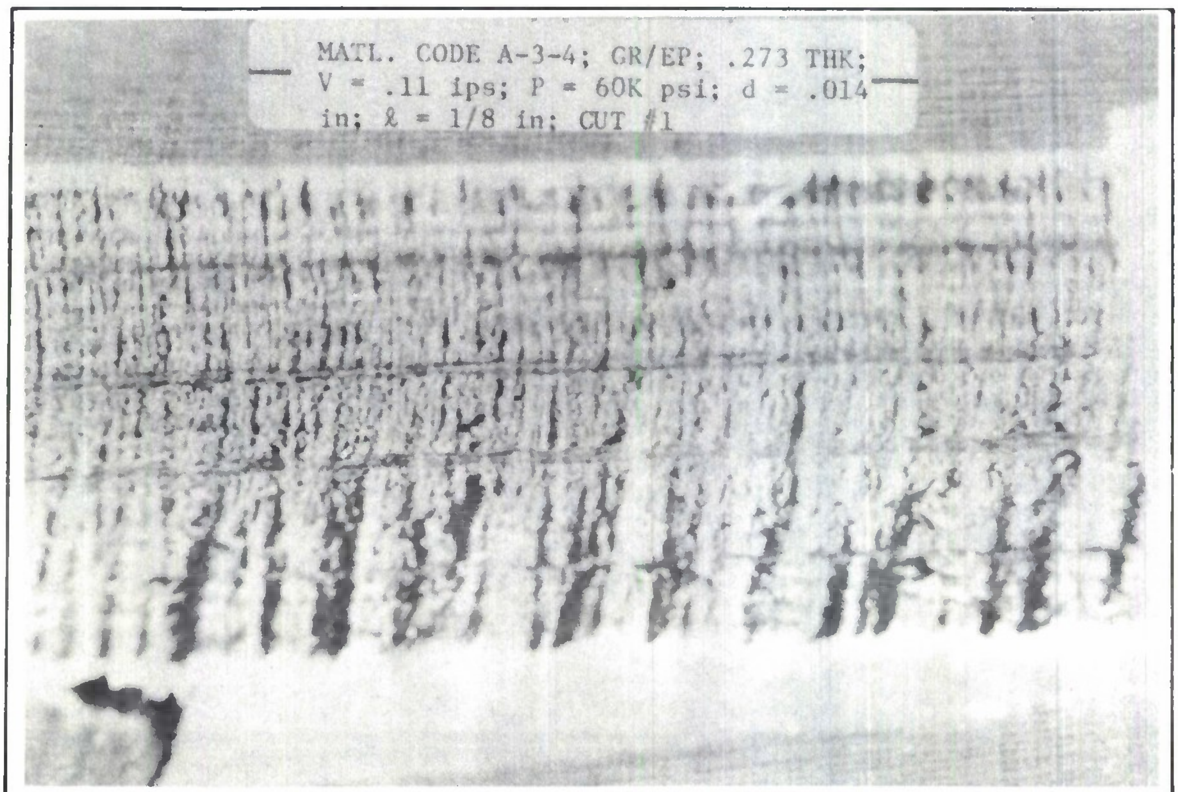


2199-110B **Figure 4-38 Optimum Cut in Cured 0.067-Inch Thick, Graphite/Epoxy Laminate (10x Mag)**

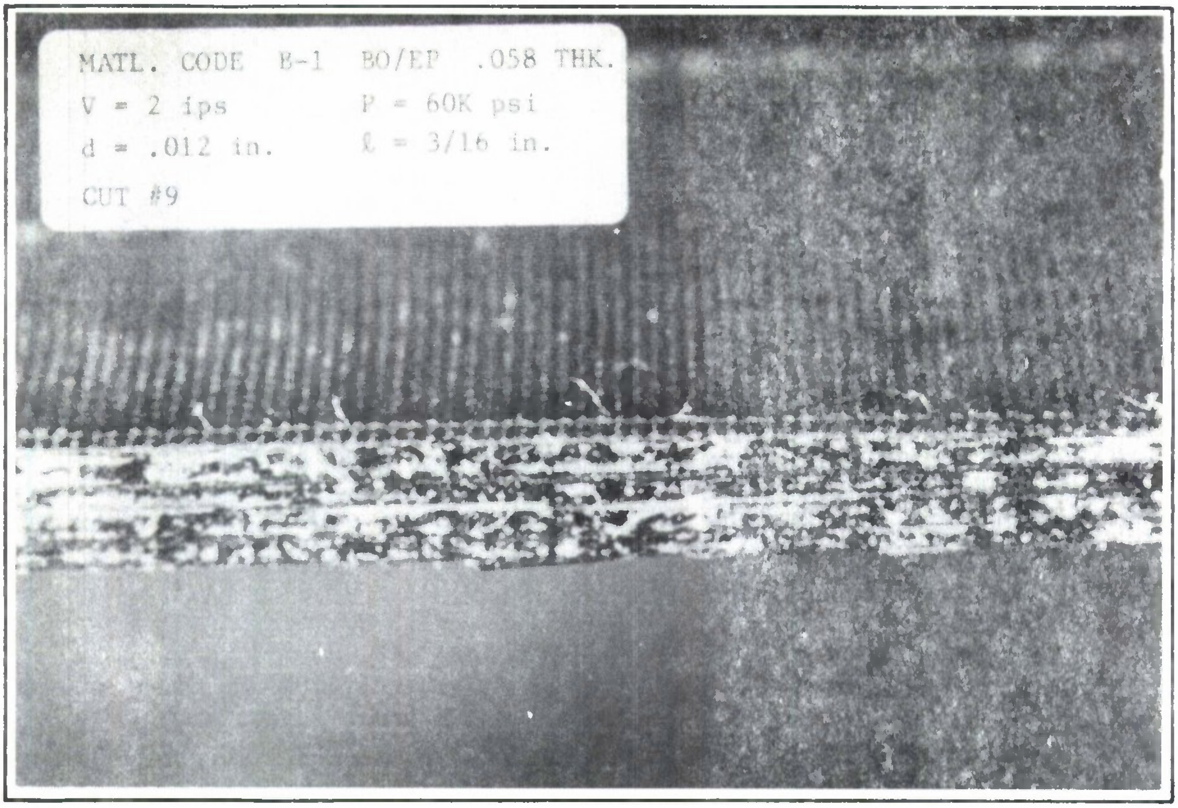


2199-111B

Figure 4-39 Optimum Cut in Cured 0.135-Inch Thick, Graphite/Epoxy Laminate (10x Mag)



2199-112B Figure 4-40 Optimum Cut in Cured 0.273-Inch Thick, Graphite/Epoxy Laminate (10x Mag)



2199-113B

Figure 4-41 Optimum Cut in Cured 0.058-Inch Thick, Boron/Epoxy Laminate (10x Mag)

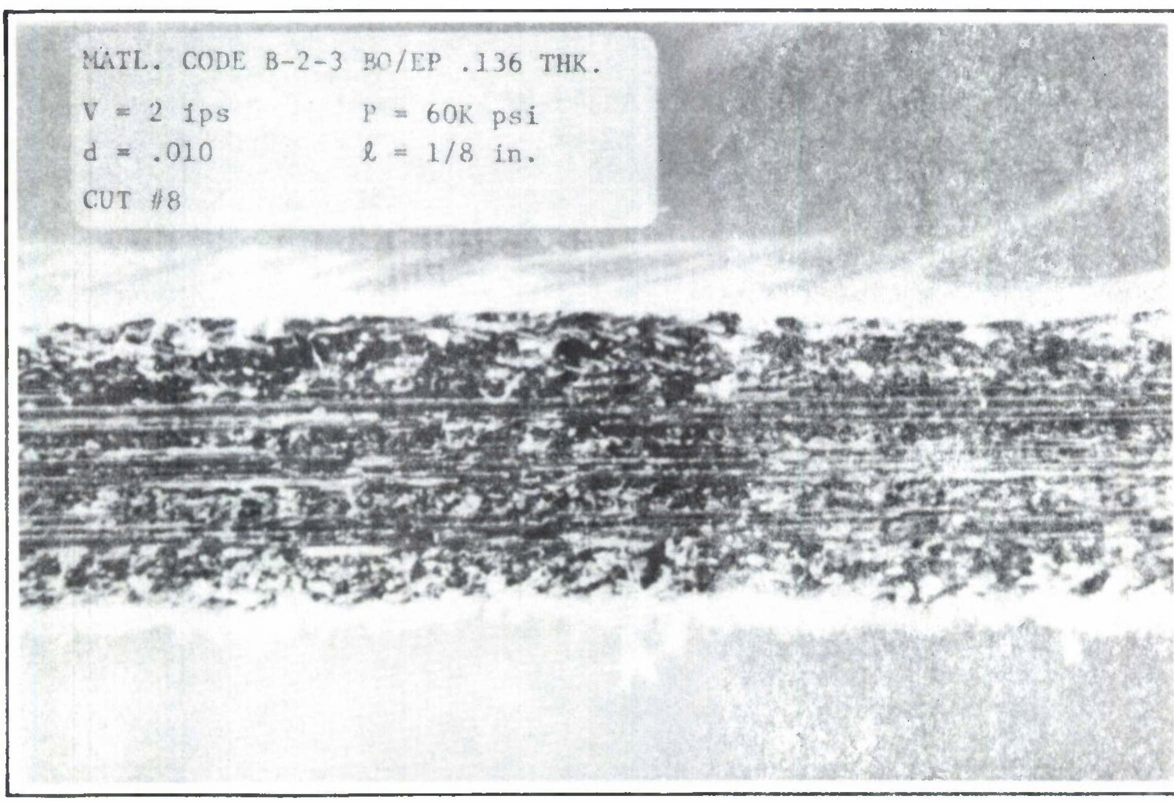
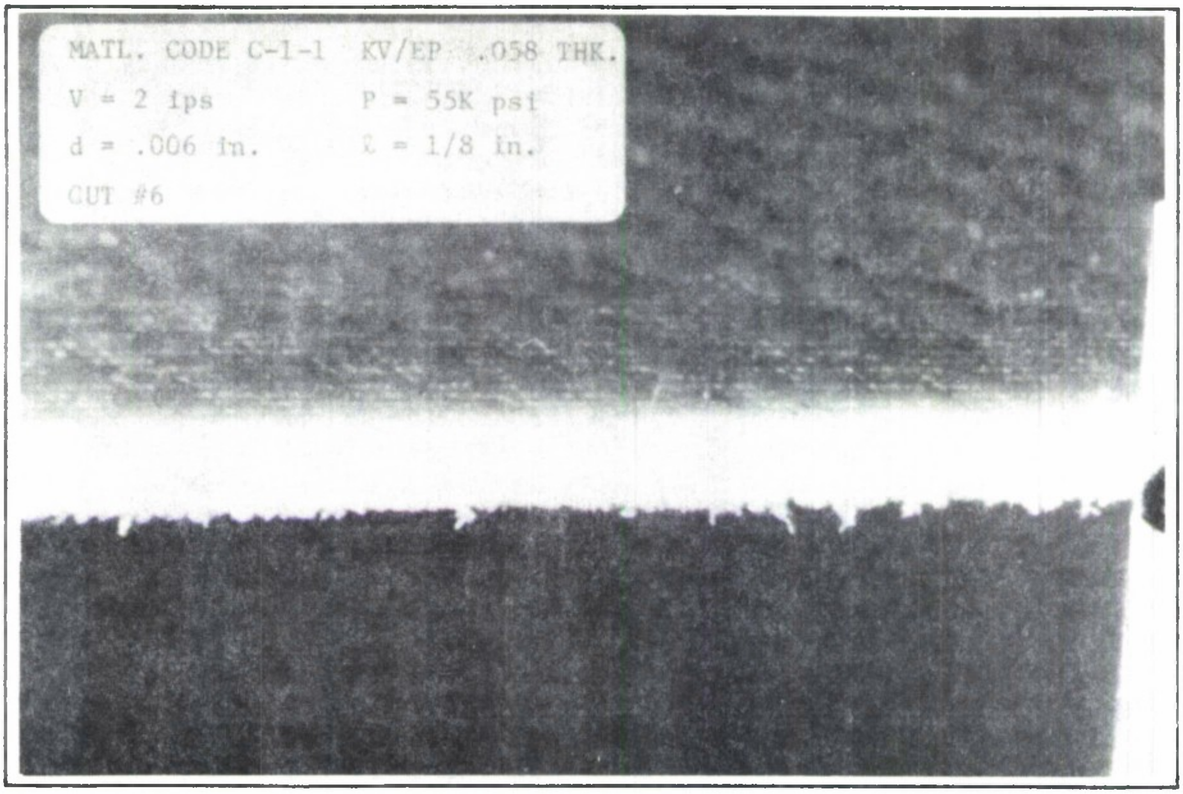


Figure 4-42 Optimum Cut in Cured 0.136-Inch Thick, Boron/Epoxy Laminate (10x Mag)

2199-114B



2199-115B

Figure 4-43 Optimum Cut in Cured 0.058-Inch Thick, Kevlar/Epoxy Laminate (10x Mag)

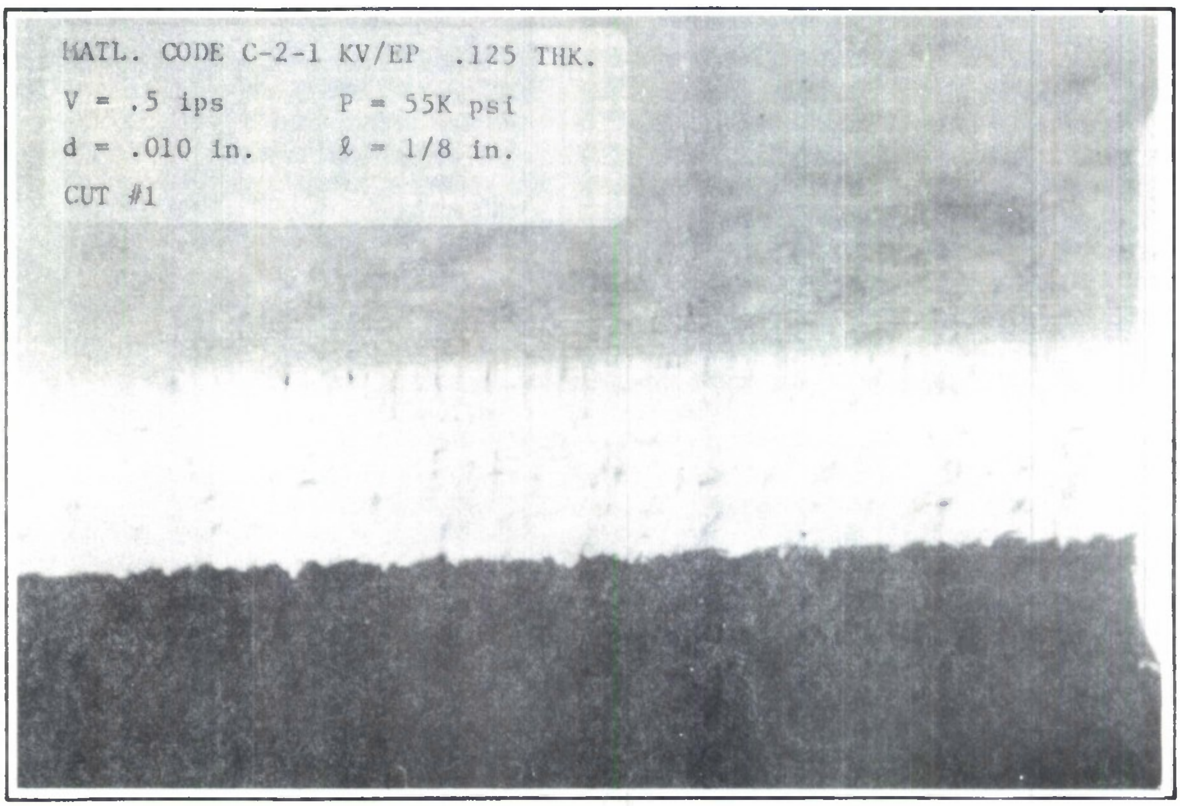


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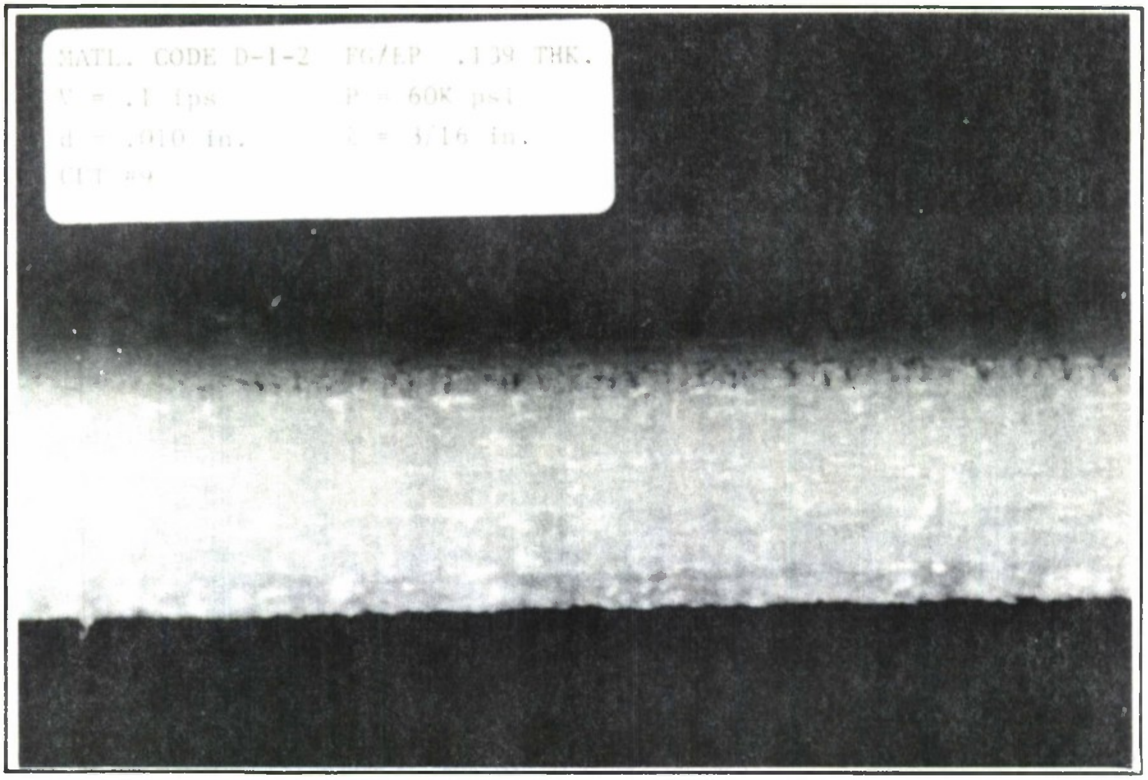
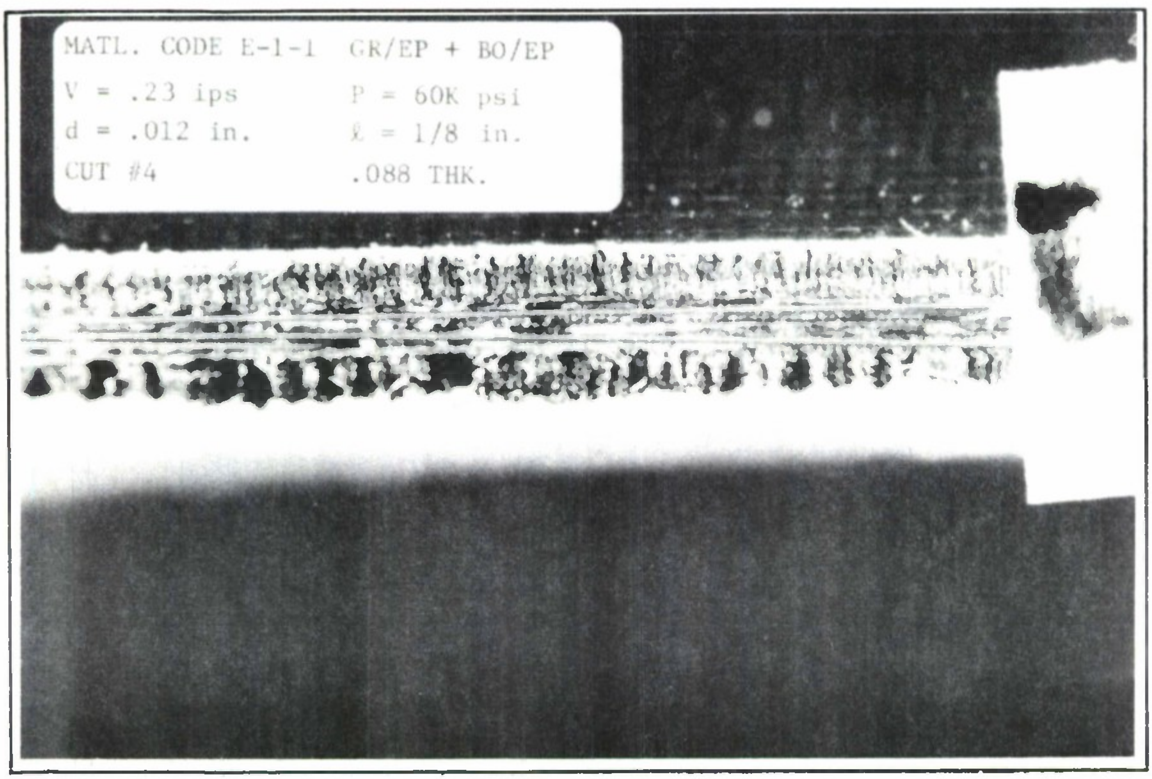
Figure 4-44 Optimum Cut in Cured 0.125-Inch Thick, Kevlar/Epoxy Laminate (10x Mag)



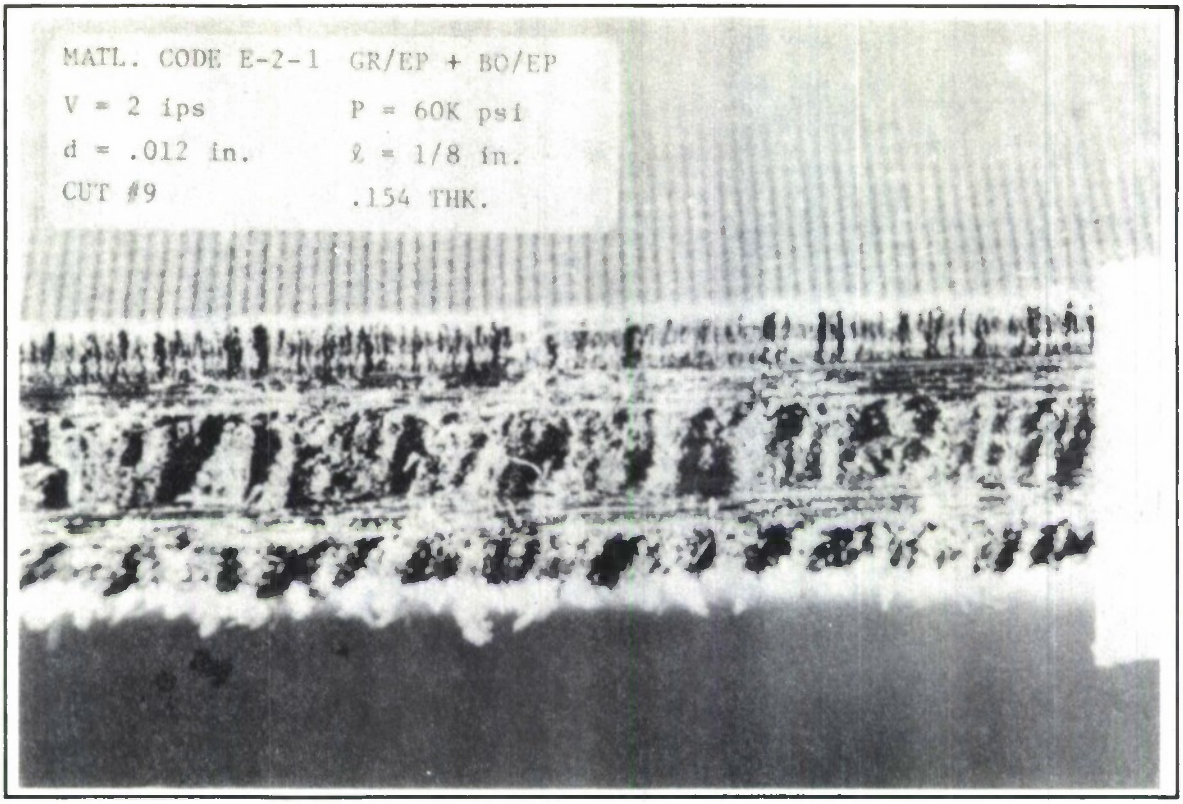
2199-117B

Figure 4-45 Optimum Cut in Cured 0.139-Inch Thick, Kevlar/Epoxy Laminate (10x Mag)



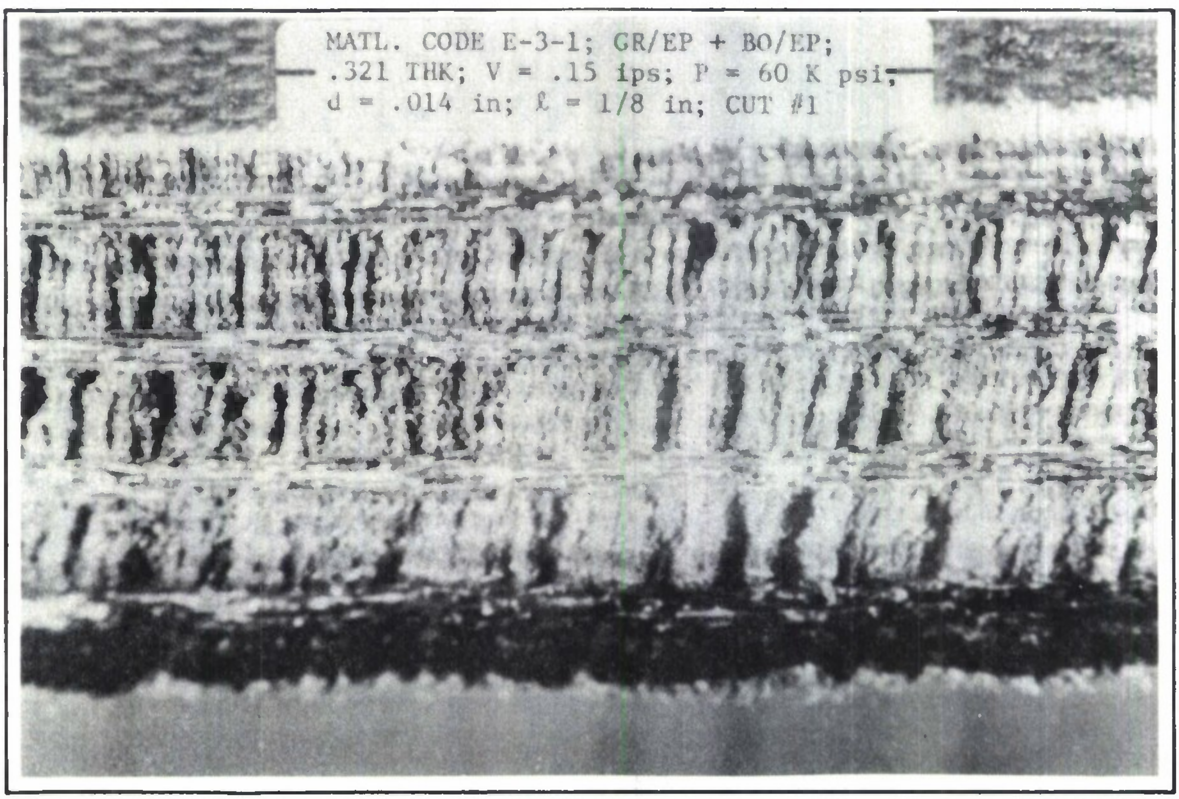
2566-019W

Figure 4-46 Optimum Cut in Cured 0.088-Inch Thick, Hybrid Boron-Graphite/Epoxy Laminate (10x Mag)



2566-020W

Figure 4-47 Optimum Cut in Cured 0.154-Inch Thick, Hybrid Boron-Graphite/Epoxy Laminate (10x Mag)



2566-021W

Figure 4-48 Optimum Cut in 0.32-Inch Thick, Hybrid Boron-Graphite/Epoxy Laminate (10x Mag)

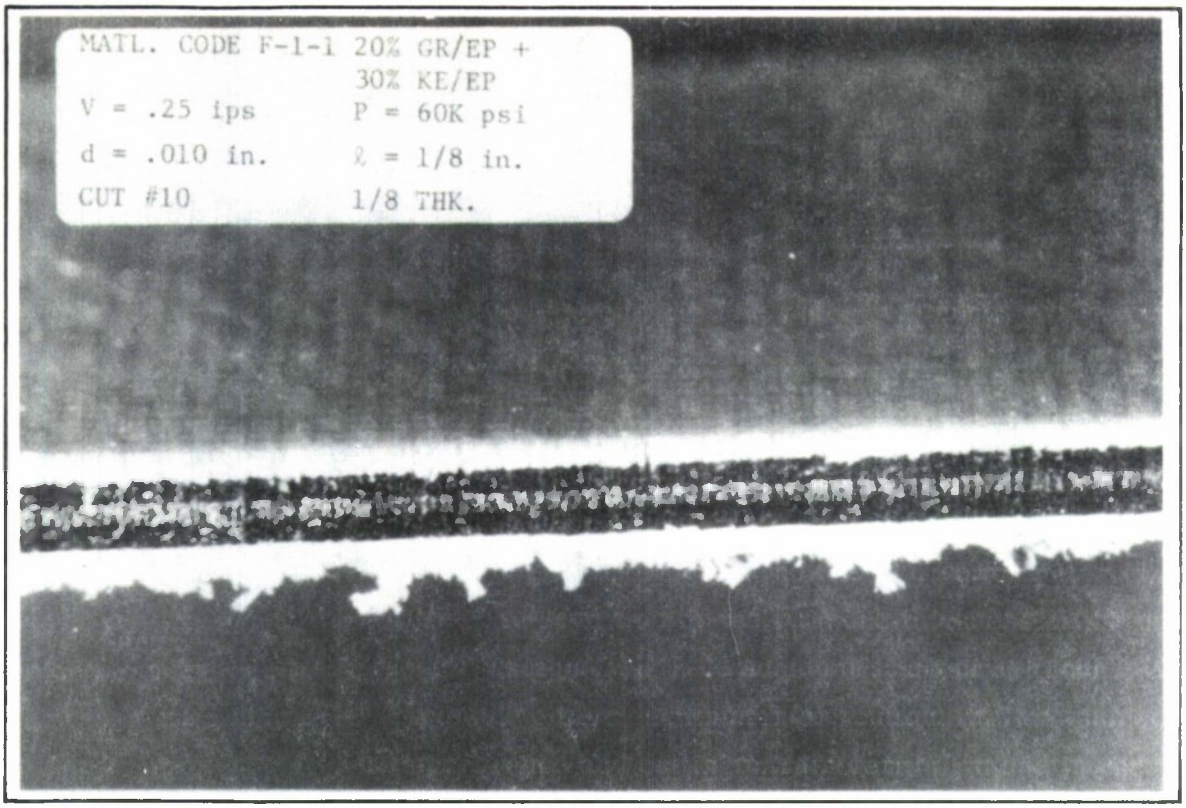


Figure 4-49 Optimum Cut in Cured 0.125-Inch Thick, Hybrid 20% Graphite – 30% Kevlar/Epoxy Laminate (10x Mag)

2199-121B

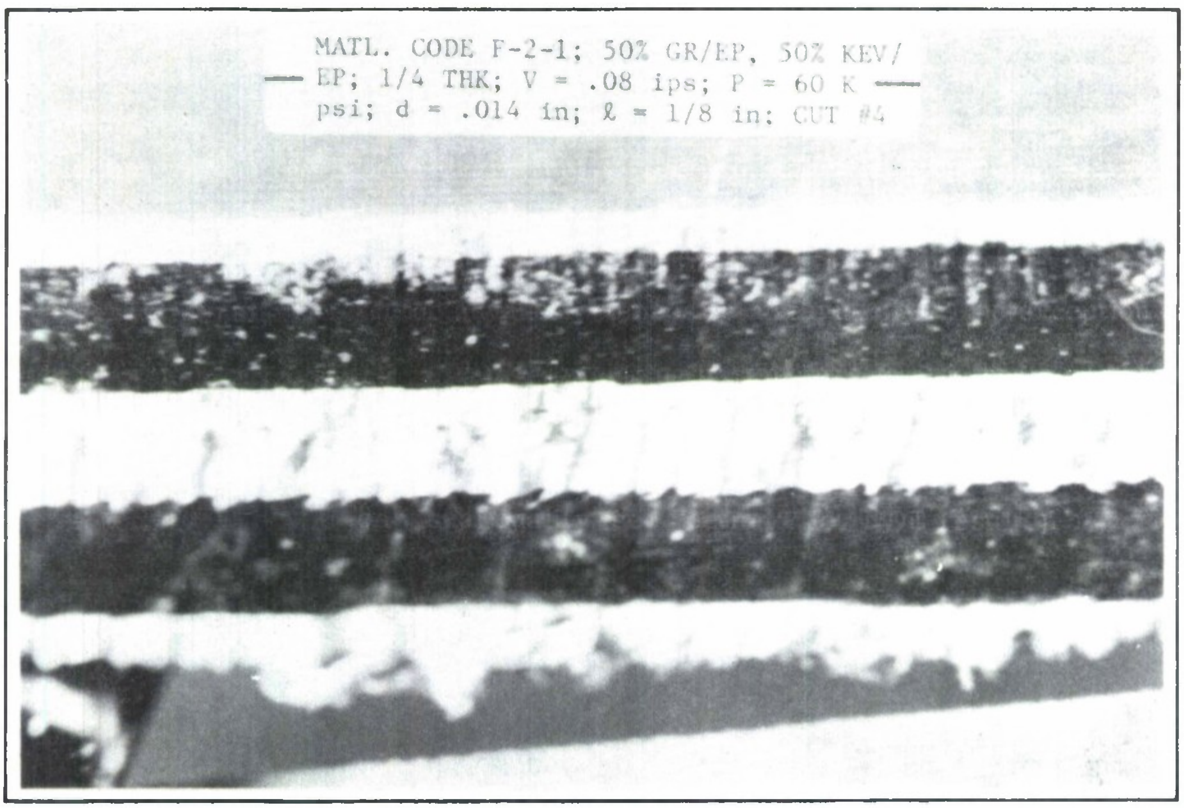


Figure 4-50 Optimum Cut in Cured 0.25-Inch Thick, Hybrid 50% Graphite – 50% Kevlar/Epoxy Laminate (10x Mag)

2199-122B

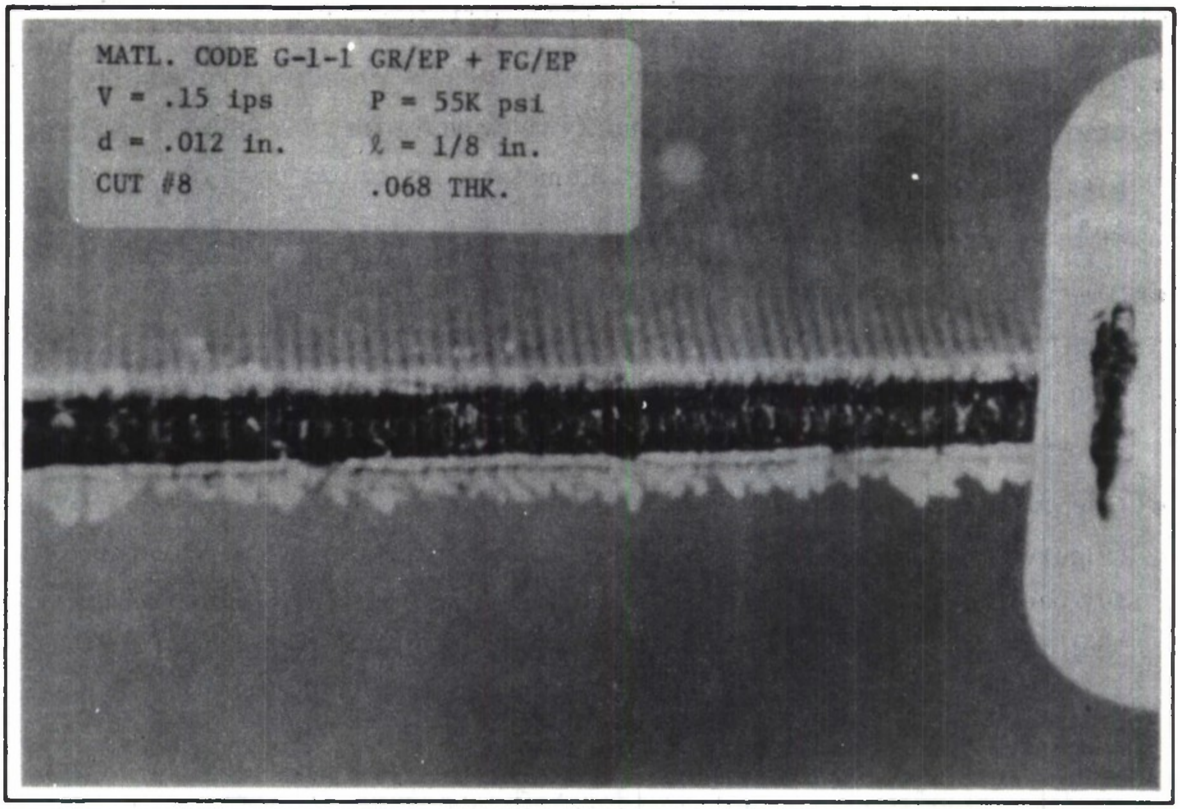


Figure 4-51 Optimum Cut in Cured 0.068-Inch Thick, Hybrid Graphite-Fiberglass/Epoxy Laminate (10x Mag)

2566-022W

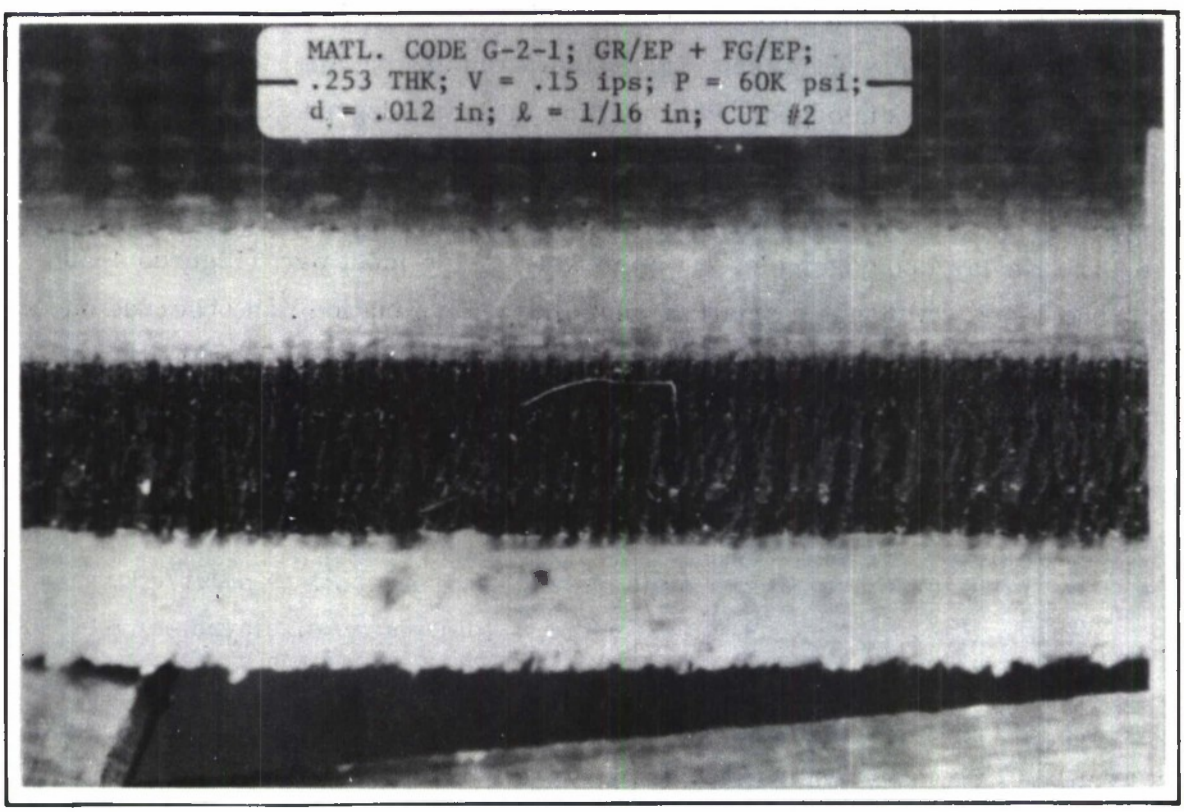


Figure 4-52 Optimum Cut in Cured 0.253-Inch Thick, Hybrid Graphite-Fiberglass/Epoxy Laminate (10x Mag)

2566-023W

Observations made during cutting of the cured materials were:

- The cured materials followed the "rules-of-thumb" observed previously for other materials, that is, the cut quality improved with increasing nozzle pressure, increasing nozzle orifice diameter, decreasing traverse speed, and decreasing material thickness and hardness.
- The softer materials cut with a better edge quality than the harder ones. The materials were, in order of decreasing hardness, boron/epoxy, graphite/epoxy, fiberglass/epoxy, and Kevlar/epoxy, with the hybrid materials occupying positions midway between the parent materials.
- The cured graphite/epoxy samples were cut with a reasonably smooth edge (Figures 4-38, 4-39 and 4-40). These samples were covered with a peel-ply backing on both sides. This backing tended to cause some problems in that it would separate from the composite due to water from the jet wedging between it and composite. The effect generally was highly localized along the line of the cut and was only of cosmetic importance in most cases.
- The boron/epoxy sample left very rough-finished cuts due to the extreme hardness of the fibers (Figures 4-41 and 4-42). When cutting in the zero-degree direction, the epoxy matrix failed adjacent to the cut (in a very localized manner) when the surface fibers running parallel to the direction of the cut were dislodged. When cutting in the 90-degree direction, many of the surface fibers along the cut were broken some distance from the line of the cut causing a very rough appearance of the cut.
- The Kevlar/epoxy samples cut quite well for the most part (Figures 4-43 and 4-44). Although a small amount of ply delamination was observed on the entry or exit sides of the cuts, this was minimized by the selection of proper cutting parameters.
- The fiberglass/epoxy samples showed some delamination like the Kevlar/epoxy samples, but cut with a reasonably smooth edge (Figures 4-45)
- The three cured hybrid composite samples (boron/epoxy, Kevlar/epoxy and fiberglass/epoxy each paired with graphite/epoxy) displayed some delamination, almost all judged to be very minor (Figures 4-46 through 4-52). The exception was the 1/4-inch-thick graphite/epoxy and fiberglass/epoxy samples which displayed serious delamination of the plies on the exit side for all sets of cutting parameters evaluated.

4.4.1.2 McCartney Tests - Additional work was performed by the McCartney Manufacturing Company that involved jet pressures up to 50 ksi; test results are summarized in Figure 4-53. Cutting parameters used in these tests included a cutting rate of up to 2.4 ips, standoff distance of 0.5 inch, jet angle of zero degrees (normal impact), and tap water with long-chain polymer additive. Although complete penetration was achieved in all cases, all specimens demonstrated visual delamination except for 0.131-inch-thick graphite/epoxy and 0.121-inch-thick Kevlar/epoxy laminates. The polymer additive apparently had the effect of increasing the cutting rate without improving quality.

4.4.1.3 IIT Research Institute - High-pressure water-jet cutting evaluations were conducted by IIT Research Institute (Reference 5) that involved jet pressures up to 100 ksi; test results are summarized in Figure 4-54. Cutting parameters used in these tests included a cutting rate of 4.5 ips, standoff distance of 0.5 inch, jet angle of zero degrees (normal impact) and tap water (no additivies). Complete penetration was achieved in all cases. It was generally found that higher jet pressures improve cutting capability. A substantial improvement in visual cut quality was obtained with boron/epoxy laminates. A cut section of a 0.450-inch-thick, hybrid graphite (48%) - boron (52%)/epoxy panel is shown in Figure 4-55.

4.4.2 Laser Cutting of Cured Composites

Cutting of cured laminates was evaluated on both low-power (250 w) and high-power (11 kw) systems.

4.4.2.1 250-Watt Laser Cutting - The laser cutting system described in Section 4.2.2 was utilized. Initial laser cutting tests were performed with cured graphite/epoxy, graphite-boron/epoxy, graphite-Kevlar/epoxy, graphite-fiberglass/epoxy, Kevlar/epoxy and fiberglass/epoxy laminates. Feed rates down to 30 ipm were evaluated. The 30-ipm feed rate was selected as the rate that offered minimum acceptable equipment utilization. Analysis of the results show generally incomplete penetration and that considerably higher power levels were required. If power is limited to 250 watts, assist-gas pressure and nozzle diameter variations offer no discernible advantages. Except for 1/16-inch-thick, graphite-Kevlar/epoxy

SPECIMAN NO.	CUT NO.	MATERIAL	THICKNESS, INCH	AMOUNT OF GR/EP, %	CUTTING RATE, IPS	CUT CONDITION (VISUAL AT 7X MAGNIFICATION
G-1	1	GRAPHITE/EPOXY	0.131	100	1.2	GOOD
G-1	2		0.131	100	2.4 (MAX)	DELAMINATED
G-2	3		0.552	100	0.4	DELAMINATED
G-2	4		0.552	100	2.0 (MAX)	DELAMINATED
G-3	5		0.875	100	0.2–0.6	NO CUT
G-3	6		0.875	100	0.2–0.6	NO CUT
B-1	7	GRAPHITE/EPOXY +	0.222	50	0.5	DELAMINATED
B-1	8	BORON/EPOXY	0.222	50	0.3	DELAMINATED
B-2	9		0.350	90	0.4	DELAMINATED
B-2	10		0.350	90	2.4	DELAMINATED
B-3	11		0.476	40	0.2 (MAX)	DELAMINATED
B-4	12	B/EP + GR/EP + FG/EP (TOP & BOTTOM)	0.516	90	0.2	DELAMINATED
FG-1	13	FIBERGLASS/EPOXY	0.143	0	0.6	DELAMINATED
FG-1	14		0.143	0	2 (MAX)	DELAMINATED
FG-2	15		0.227	0	0.6	DELAMINATED
FG-2	16		0.227	0	1.2 (MAX)	DELAMINATED
FG-3	17	FIBERGLASS/EPOXY +	0.260	40	0.6	DELAMINATED
FG-3	18	GRAPHITE/EPOXY	0.260	40	1.2 (MAX)	DELAMINATED
K-1	19	KEVLAR/EPOXY	0.121	0	0.8	GOOD
K-1	20		0.121	0	1.6 (MAX)	DELAMINATED
K-2	21	KEVLAR/EPOXY +	0.277	60	0.6	DELAMINATED
K-2	22	GRAPHITE/EPOXY	0.277	60	0.8 (MAX)	DELAMINATED

CONDITIONS:
- STRAIGHT CUTS
- PRESSURE: 40,000–50,000 PSI
- STAND-OFF: 0.50 INCH
- NOZZLE DIAMETER: 0.010 INCH

Figure 4-53 Summary of Water-Jet Cutting of Cured Composites by the McCartney Manufacturing Company

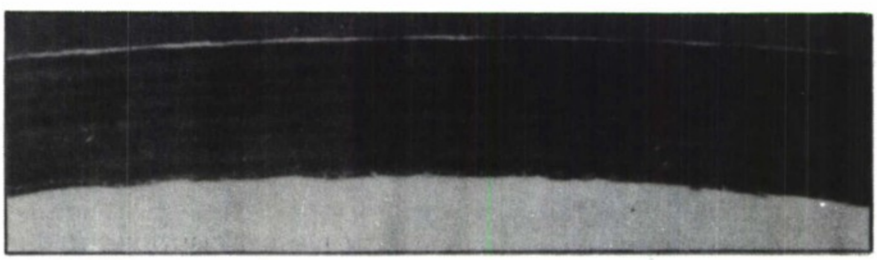
2199-125B

SPECIMEN NO.	MATERIAL	THICKNESS, INCH	% GRAPHITE	NOZZLE DIAMETER, mm	JET PRESSURE, psi	CUT CONFIGURATION
1	GRAPHITE/EPOXY	0.065	100	0.24	81,000	ARC CUT + HOLE
2	GRAPHITE/EPOXY	0.090	100	0.24	81,000	ARC CUT + HOLE
3	GRAPHITE/EPOXY	0.181	100	0.40	100,000	ARC CUT + HOLE
4	GRAPHITE/EPOXY	0.541	100	0.40	100,000	ARC CUT + HOLE
5	GRAPHITE/EPOXY	0.750	100	0.40	100,000	STRAIGHT CUT
6	BORON/EPOXY	0.136	0	0.24	80,000	ARC CUT + HOLE
7	FIBERGLASS/ EPOXY	0.275	0	0.40	80,000	ARC CUT + HOLE
8	GRAPHITE/EPOXY + BORON/EPOXY	0.354	90	0.40	99,500	ARC CUT + HOLE
9	GRAPHITE/EPOXY + BORON/EPOXY	0.450	48	0.40	99,000	ARC CUT + HOLE

(Note: Cutting speed of 270IPM was used for all samples)

2566-126B

Figure 4-54 Summary of Water-Jet Cutting of Cured Composites by IIT Research Institute



2566-024W

Figure 4-55 Cross-Section of Water-Jet Cut, 0.450-Inch Thick, Hygrid Graphite-Boron/Epoxy Panel

laminates in which separation occurred at a feed rate of 30 ipm (but not at 60 ipm) and 0.035-inch-thick Kevlar/epoxy which was cut at 150 ipm, none of the other advanced composite laminates could be completely penetrated at a feed rate of 30 ipm.

4.4.2.2 High-Power Laser Cutting - Additional testing was performed at United Technologies Research Laboratory with power levels up to 11 kilowatts. A summary of the materials evaluated, laser parameters, and cutting results is presented in Figure 4-56. In general, these results showed graphite/epoxy and its hybrids require minimum power levels of 8 kilowatts, cutting speed decreases with thickness, and thermal damage is an inverse function of cutting speed. Photomacrographs of representative laser-trimmed graphite/epoxy laminates are shown in Figure 4-57.

MATERIAL	AMOUNT OF GR/EP, %	MATERIAL THICKNESS, IN.	POWER, KW	SPEED, IPM	EXTENT OF THERMAL DAMAGE TO EDGE, IN.
GRAPHITE/ EPOXY	100	0.066	8	120	0.060
GRAPHITE/ EPOXY	100	0.197	8	30	0.281
GRAPHITE/ EPOXY+BORON/ EPOXY	60	0.266	8	30	0.156
GRAPHITE/EPOXY + BORON/EPOXY	90	0.357	11	25	0.156
GRAPHITE/ EPOXY + FIBERGLASS/ EPOXY	50	0.260	8	40	0.050
KEVLAR/EPOXY	0	0.120	3	120	0.050

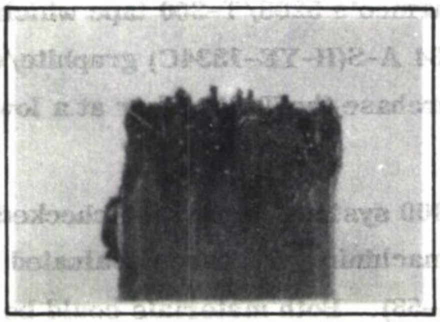
CONDITIONS:

- EQUIPMENT: MULTI-KW, CO_2 LASER WITH GAUSSIAN ENERGY DISTRIBUTION OUTPUT BEAM-15 KW (MAX)
- PERISCOPE: TWO 6-INCH DIAMETER MIRRORS (FLAT)
- EXTEND OPTICS: 20-INCH FOCAL LENGTH, 90° OFF-AXIS PARABOLIC FOCUSING MIRROR AND A FLAT COPPER TURNING MIRROR.
- JET ASSIST: COPPER NOZZLE LOCATED ABOUT 1/4 INCH ABOVE WORKPIECE AT 45° ANGLE
- ASSIST GAS: 150-PSI N_2

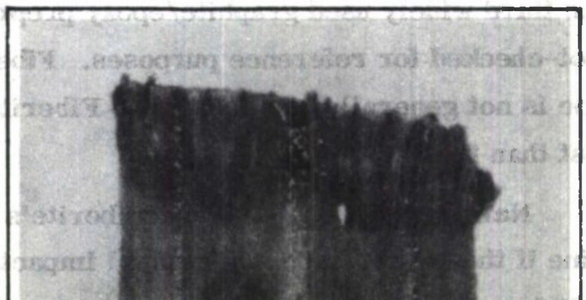
2199-128B **Figure 4-56 Summary of High-Power Laser Cutting of Cured Composites**

Graphite/Epoxy
(0.066-In. Thick)

Graphite/Epoxy
(0.197-In. Thick)

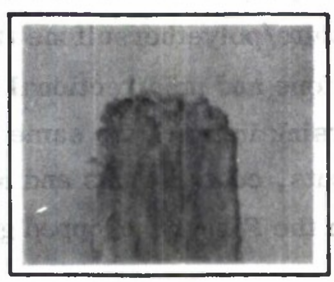


Graphite/Epoxy + Boron/Epoxy
(0.266-In. Thick)



Graphite/Epoxy + Boron/Epoxy
(0.357-In. Thick)

Graphite/Epoxy + Fiberglass/Epoxy
(0.260-In. Thick)



Kevlar/Epoxy
(0.120-In. Thick)

2566-025W

Figure 4-57 Photomacrographs of Typical Laser-Cut Laminates (5x Mag)

4.5 ALTERNATE COMPOSITE SYSTEMS AND NEW MATERIAL FORMS

4.5.1 Alternate Composite Systems

The standard boron/epoxy prepreg used to fabricate the covers of the F-14A horizontal stabilizer is Avco's 5505-III tape. An alternate system is 3 M's SP-290 tape (4 mils thick) which incorporates boron fibers produced by Composite Technology, Inc., and impregnated by the 3 M Company. Since the Avco tape meets all production needs and specification requirements at a lower cost than the 3 M tape, it is used exclusively.

The standard graphite/epoxy prepreg used by Grumman is Hercules 3501-5A/A-S tape. Since the 3501-5A/A-S system is very similar to the 3501-6 system, which has been qualified for several recent production programs, additional testing was not required. The third widely used graphite/epoxy prepreg is Narmco's 5208/T-300 tape which was spot-checked for reference purposes. Fiberite's 934 A-S(H-YE-1334C) graphite/epoxy tape is not generally used, because Fiberite can purchase the T-300 fiber at a lower cost than the 934/A-S prepreg.

Narmco's 5208/T-300 and Fiberite's 934/T-300 systems were spot-checked to determine if they would have any unusual impact on the machining processes evaluated -- radial sawing and drilling/countersinking (Figure 4-58). Both materials could be cut and drilled/countersink as readily as the basic Hercules 3501-A/S material.

4.5.2 New Material Forms

The potential impact of near-term and future material forms on the data generated using the baseline materials was spot-checked. The new material forms screened included Fiberite's HY-E/7534 graphite/epoxy mat, which consists of chopped graphite fibers in an epoxy resin matrix, Fiberite's HMF-330B34 woven graphite/epoxy, and woven graphite/polyethersulfone (thermoplastic matrix). The woven graphite/polythersulfone and unidirectional graphite/polysulfone materials could be cut, drilled and countersink in much the same manner as the basic Hercules 3501/A-S material. Excellent cuts, countersinks and holes without breakout (when backup was not used) were produced in the Fiberite chopped graphite fiber material (Figure 4-58).

MATERIAL	TYPE	THICK-NESS, W.	PROCESS	CUTTING PARAMETERS			TOOL MATL	COOLANT MIST	EDGE OR HOLE C'SINK QUALITY	COMMENTS
				SFM	RPM	IPR				
GRAPHITE/EPOXY	NARMCO 5208/T300	0.084	RADIAL SAW	7154			DIAMOND CDATED, 60 - B0 GRIT	YES	GOOD	• CUTS SAME AS HERCULES 3501 A-S
			DRILL C'SINK		6000	0.001	CARBIDE	NO	EXCELLENT	• DRILLS SAME AS HERCULES 3501-A-S BREAKOUT WITH-OUT BACKUP
	FIBERITE 934/T-300 HY-E-1034	0.143	RADIAL SAW	7154			DIAMOND COATED, 60 - B0 GRIT	YES	GOOD	SAME AS ABOVE
			DRILL C'SINK		6000	0.001	CARBIDE	NO	EXCELLENT	SAME AS ABOVE
	FIBERITE HY-E/7534 CHOPPED FIBER	0.226	RADIAL SAW	7154			DIAMOND COATED, 60 - B0 GRIT	YES	EXCELLENT	SAME AS ABOVE
			DRILL C'SINK		6000	0.001	CARBIDE	ND	EXCELLENT	• NO BREAKOUT WITHOUT BACKUP
GRAPHITE/POLYSULFONE	HERCULES GR (3004-AS) TAPE	0.085 (UNI-DIREC-TIDNAL LAY-UP)	RADIAL SAW	7154			DIAMOND COATED, 60 - B0 GRIT	YES	GOOD	• CUTS SAME AS ABOVE; SAW LOADS UP WITH RESIN BUT CAN BE REMDVEO BY DRESSING BLADE; SLIGHT BREAKOUT DN BACKSIDE CUTTING CROSSPLY
			RADIAL SAW	7154			HSS 126 TDOTH	YES	VERY GOOD	• CUTS WELL BUT SAWS DULLS RAPIDLY; SLIGHT BREAKOUT DN BACKSIDE CUTTING CROSSPLY
			DRILL C'SINK		6000	0.001	CARBIDE	NO	EXCELLENT	• SLIGHT BREAKOUT WITHOUT BACKUP
GRAPHITE/POLYETHER-SULFONE	FIBERITE HMF-330B34 WOVEN	0.085	RADIAL SAW	7154			DIAMDND CDATED, 60 - B0 GRIT	YES	GOOD	• BREAKOUT ON BACKSIDE; SAW LOADS UP WITH RESIN BUT CAN BE REMOVED BY DRESSING BLADE
				7154			HSS 126 TOOTH	YES	VERY GDOD	• SLIGHT BREAKDUT ON BACKSIDE; SAW DRILL RAPIDLY
				7154			DIAMOND SINTEREO 60 - B0 GRIT	YES	VERY GOOD	• SLIGHT BREAKOUT ON BACKSIDE
			DRILL C'SINK		6000	0.001	CARBIDE	NO	EXCELLENT	• BREAKOUT WITHOUT BACKUP

2566-026W

Figure 4-58 Summary of Alternate Graphite and New Material Systems

Section 5

PHASE II - DRILLING

The objective of this phase was to document the state-of-the-art of low-cost manufacturing methods for drilling graphite/epoxy and hybrids thereof. The primary baseline structure and production experience used was the B-1 horizontal stabilizer. This phase consisted of three tasks: compilation of existing data, supplemental drilling data and assembly drilling.

5.1 COMPILATION OF DATA

A primary task in this phase of the program was to document the existing manufacturing methods for drilling graphite/epoxy laminates and hybrids thereof. A substantial amount of information was obtained through compilation of data and production experience gained on the B-1 horizontal stabilizer. Other sources being utilized are published Metcut data (Reference 6), Air Force development contracts (Reference 7) and industry IR&D programs (Reference 12). When the program was completed, initially compiled data were upgraded to reflect new and/or improved drilling procedures or developments which occurred in both the supplemental and assembly drilling tasks.

A summary matrix chart for high-speed steel and carbide drills is shown in Figure 5-1. It should be noted that high-speed steel cutting tools generally yield poor quality holes and cutting life. Normally, only two holes of acceptable quality were achieved in drilling graphite/epoxy. These tool materials, therefore, are not recommended for production applications. The one notable exception is the Jancy HSS counterbore which can be effectively used to drill Kevlar/epoxy.

The chart shown in Figure 5-1 is based on workpiece and operational requirements. Drill speed is obtained directly from the chart. Specific feeds are obtained from Figure 5-2 and the data presented in Figure 5-1. Wear land development is similarly selected in Figure 5-3. If the operation is manual drilling, Figure 5-4 is used. A similar summary chart is presented for metal matrix tools (Figure 5-5) with application primarily to boron/epoxy and hybrids containing boron/epoxy.

		HSS (M2, M77, M10, M33, M42)								CARBIDE (C2 or C6)							
		CORE DRILL (OFFHAND)	POWER FEED	OFF HAND DRILL	DRILL C'SINKING (MACH)	C'SINKING (OFFHAND)	C'BORING (OFFHAND)	REAMING (OFFHAND)	REAMING (MACH.)	CORE DRILL (OFFHAND)	POWER FEED	OFF HAND DRILL	DRILL C'SINKING (MACH.)	C'SINKING (OFFHAND)	C'BORING (OFFHAND)	REAMING (OFFHAND)	REAMING (MACH.)
Graphite/Epoxy	FEED SPEED (SFM) WEAR	LH 100/125 H	I 175/225 H	MH 200/250 H	VL 75 H	HH 50/100 LA	HH 200 H	LH 100/120 H	L 100/120 H	LH 200/250 LA	VL 900/1050 L	LH 300/500 LA	VL 900/1050 L	HH 250/275 LA	HH 500 LA	LH 200/250 L	L 400/500 L
60% FG/EP +40% GR/EP	FEED SPEED (SFM) WEAR	LH 100/125 H	VL/L 75/100 H	MM 125/150 H	VL/L 40/50 H	MH 50 H	MH 100 H	LH 60/75 H	L 60/75 H	LH 125/150 LA	VL/L 300/400 L	LH 250/300 L	VL/L 400/500 L	HH 225/275 LA	HH 450/550 LA	LH 125/150 LA	L 200/250 L
Fiberglass/ Epoxy	FEED SPEED (SFM) WEAR	LH 60/75 H	VL/L 80/100 H	MH 125/150 H	VL/L 40/50 H	MH 50 H	MH 100 H	LH 60/75 H	L 60/75 H	LH 125/150 L	VL/L 300/400 L	LH 250/300 L	VL/L 225/275 L	LH 225/275 L	MH 450/550 L	LH 125/150 LA	L 150/200 L
GR/EP+AL LAM (AL>030)	FEED SPEED (SFM) WEAR	MH 120 H	M 200 H	MH 200 H	M 150 H			MH 100/120 H	M 100/120 H	MH 200 A	M 250 LA	MH 300 A	M 150 LA			MH 200 A	M 200 LA
GR/EP+AL ALLOY (AL≤030)	FEED SPEED (SFM) WEAR	LH 100/125 H	I 175/225 H	LH 200/250 H	L 200/250 H			LH 100/120 H	L 100/120 H	LH 200/250 LA	L 250/300 L	LH 300/500 L	LH 300/500 L			LH 200/240 LA	L 200/240 LA
GR/EP+FG LAM (¼+010/.014)	FEED SPEED (SFM) WEAR	LH 100/125 H	L 150/200 H	LH 200/250 H	L 75 H	HH 50/100 H	MH 125/150 H	LH 100/120 H	L 100/120 H	LH 200/250 LA	L 300/400 L	LH 300/500 LA	VL 400/500 L	HH 225/275 LA	HH 400/500 LA	LH 200/240 L	L 200/240 L
GR/EP+Ti LAM (Ti ≤ .030)	FEED SPEED (SFM) WEAR	MH 50/60 H	I 60/75 H	MH 100/120 H	I 50 H			MH 50/60 H	I 50/60 H	MH 125/150 A	I 125/150 LA	MH 150/200 A	I 100/120 LA			MH 125/150 A	I 125/150 A
GR/EP+Ti LAM (Ti>.030)	FEED SPEED (SFM) WEAR	HH 15/20 H	I 20/30 H	HH 20/30 H	I 10/15 H			HH 15/20 H	I 15/20 H	HH 60/80 A	I 70/100 A	HH 70/100 HA	I 80/85 A			HH 60/80 HA	I 75 LA

NOTE: COOLANT REQUIRED ONLY WHEN DRILLING COMPOSITES INTERLEAVED WITH/OR BONDED TO TITANIUM.

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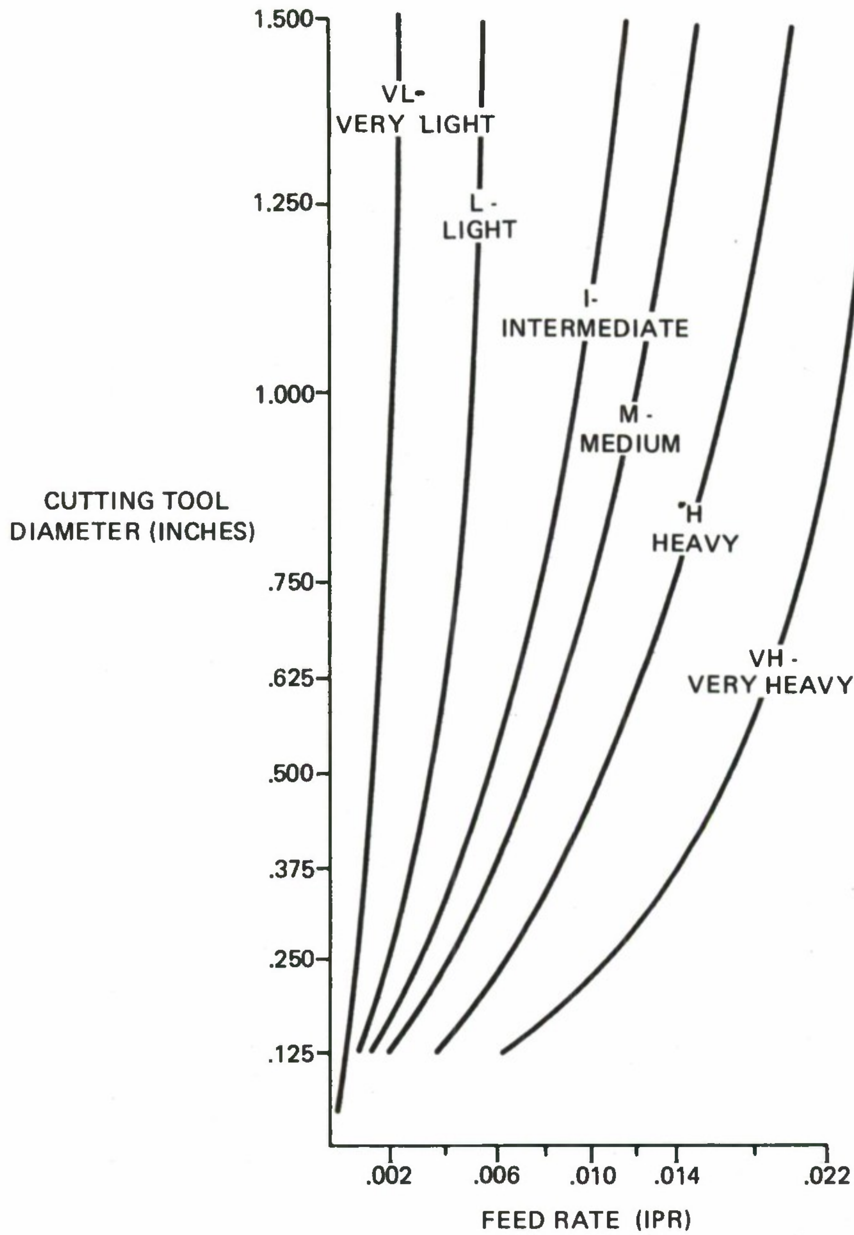
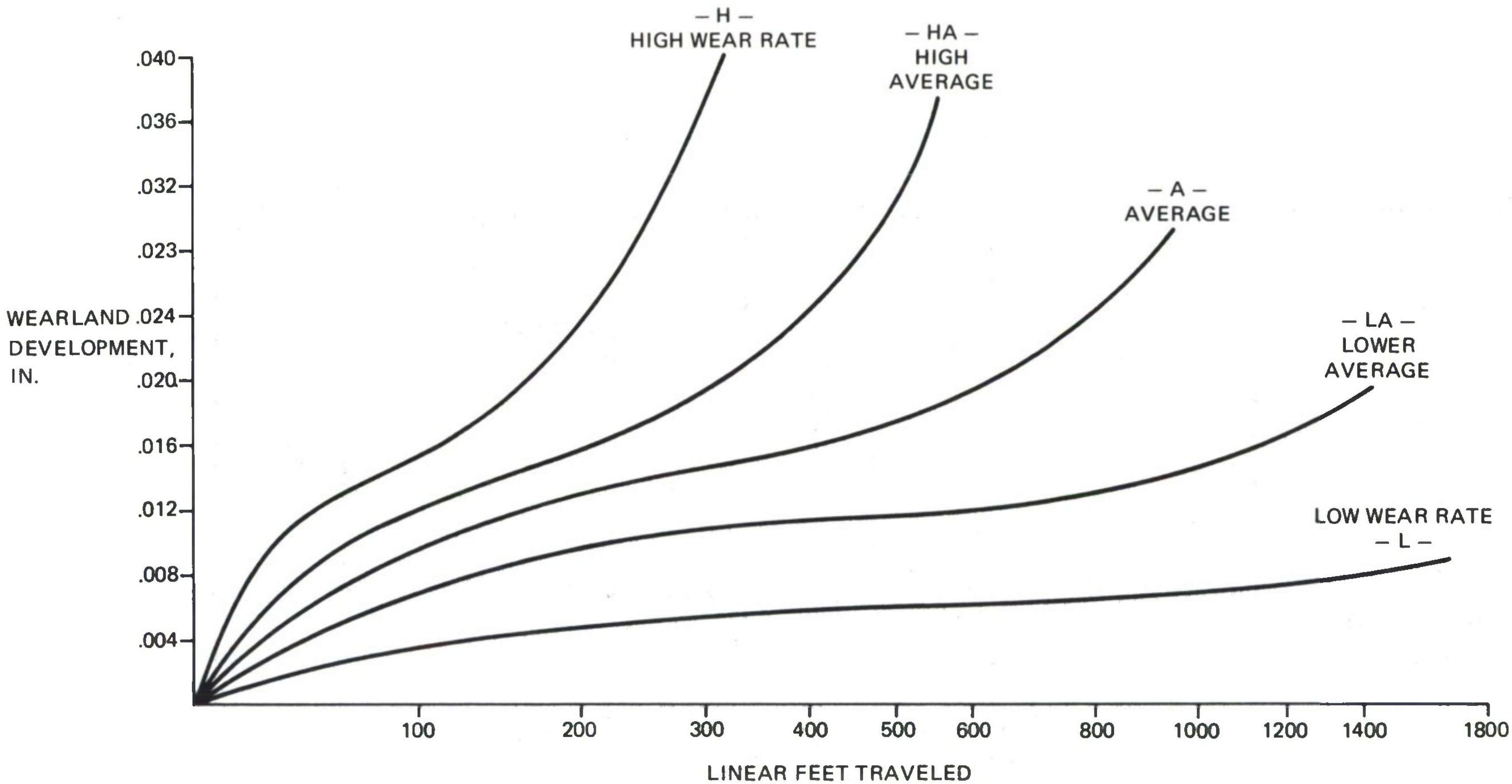
Figure 5-1 Summary Matrix of Compiled Drilling Data



2566-089W

Figure 5-2 Drilling Feed Rate Selection Chart



256^-029W

Figure 5-3 Effect of Linear Feet Traveled on Wear Land Development

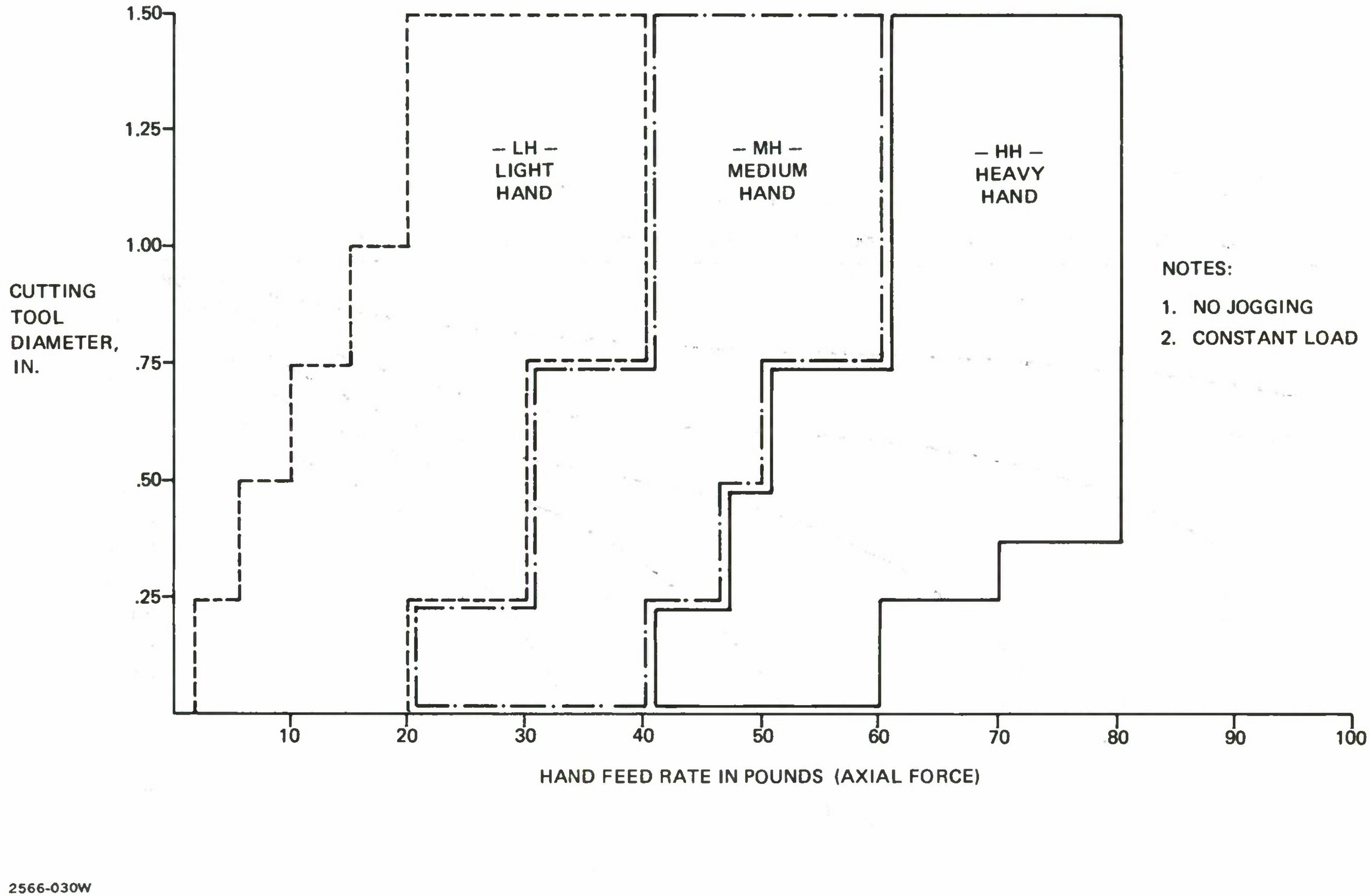


Figure 5-4 Diameter-Hand Feed Rate Selection Chart

MATL	OPERATING PARAMETER	U/S CORE[1,2] DRILLING[4]	U/S DRILL[1,2] C'SINKING[3,6]	U/S[1,2] C'SINKING[3]	POWER FEED CORE DRILLING[2]	REAMING	HONING[2]	OFF-HAND C'SINKING[3]
GRAPHITE/EPOXY	SIZE (IN)				.190 – .50	.190 – .50	.190 – .50	.190 – .50
	GRIT				60 – 80	100 – 120	220 AVG.	60 – 100
	CONCEN.				100	100	100	100
	FEED				1"/MIN	LH	LH	LH
	SPEED (RPM)				4500 – 3500	2500 – 2000	500 – 400	500 – 450
	LIFE (NO. HOLES)				300 MIN	250 – 500	250 – 400	300 MIN
30, 40 & 50% B-G/E	SIZE (IN)	.190 – .375	.190 – .500	TO .37	.190 – .50	.190 – .500	.190 – .500	.190 – .500
	GRIT	60 – 80	60 – 80	80 – 100	60 – 80	100 – 120	220 AVG	60 – 100
	CONCEN.	100	100	100	100	100	100	100
	FEED	1-1 1/4" MIN/AIR	1-1 1/4" MIN/AIR	1-1 1/4" MIN/AIR	1"/MIN	LH	LH	LH
	SPEED (RPM)	3500 – 2500	4000 – 2250	4250 – 3250	4500 – 3500	2500 – 2000	500 – 400	500 – 400
	LIFE (NO HOLES)	200 –400	75 – 150	75 – 150	100 – 200	100 – 200	75 – 150	30 – 60[5]
BORON/EPOXY	SIZE (IN)	.190 – .375	.190 – .250	TO .37	.190 – .50	.190 – .500	.190 – .500	.190 – .500
	GRIT	80 – 100	60-80DR/ 80-100 CSK	80 – 100	60 – 80	100 – 120	220 AVG.	60 – 80
	CONCEN.	100	100	100	100	100	100	100
	FEED	GRAVITY-2.4"/MIN	GRAVITY	GRAVITY	1"/MIN	LH	LH	LH
	SPEED (RPM)	5400 – 2700	5500 – 3600	4250 – 3250	5000 – 3000	2500 – 2000	500 – 400	500 – 400
	LIFE (NO HOLES)	150 – 300	50 – 100	50 – 100	75 – 150	75 – 150	50 – 100	20 – 40[5]

NOTES:
1. U/S FREQ–20 KHz
2. WATER COOLANT
3. PLATED COUNTERSINK
4. SINTERED CONSTRUCTION
5. FINISHING OPERATION
6. LIFE DEPENDS ON C'SINK.

2566-173W

Figure 5-5 Summary of Metal-Matrix Diamond-Tool Operating Parameters

5.2 SUPPLEMENTAL AND FUNCTIONAL DRILLING DATA

New cutting tool technology could improve the cost-effectiveness of drilling methods. In the case of limited testing with graphite/epoxy, refined drilling parameters might accomplish the same purpose. Supplemental and functional tests were performed to bring this about.

Drilling tests were conducted with the Dumore Series 24 machine (Figure 5-6). This machine has infinitely variable feeds and variable speeds up to 6000 rpm. The air-over-oil feed mechanism is similar to that for the Winslow Spacematic portable drilling machine. Drilling tests at speeds from 10,500 and 21,000 rpm were conducted on Gardner-Denver portable machines (Figure 5-7).

Wear land measurements were taken, where applicable, as shown in Figure 5-8. This measurement was taken at the primary cutting edge relief surface at the outboard corner. The wear land was the amount of erosion on the cutting lip surface, not that which was worn away. In order to evaluate drill wear in terms of a baseline common to all tests, the linear feet traveled by the drill tip was computed. This compensated for feed, diameter, material thickness, and number of holes drilled. It was recognized that these variables were not directly proportional to each other; however, this method was selected in an effort to provide some standardization between tests. Unless otherwise noted, tool life criterion was a maximum 0.006-inch wear land development.

5.2.1 New Cutting Tool Technology

A host of new cutting tools were selected for evaluation. These included inserted, sintered-diamond, diamond-coated, diamond-impinged, electroformed, Borazon, and alternate drill point configurations as shown in Figures 5-9 and 5-10. 5-10.

A summary of all supplemental drilling tests is given in Figure 5-11. In general, tests showed the following drills to have potential:

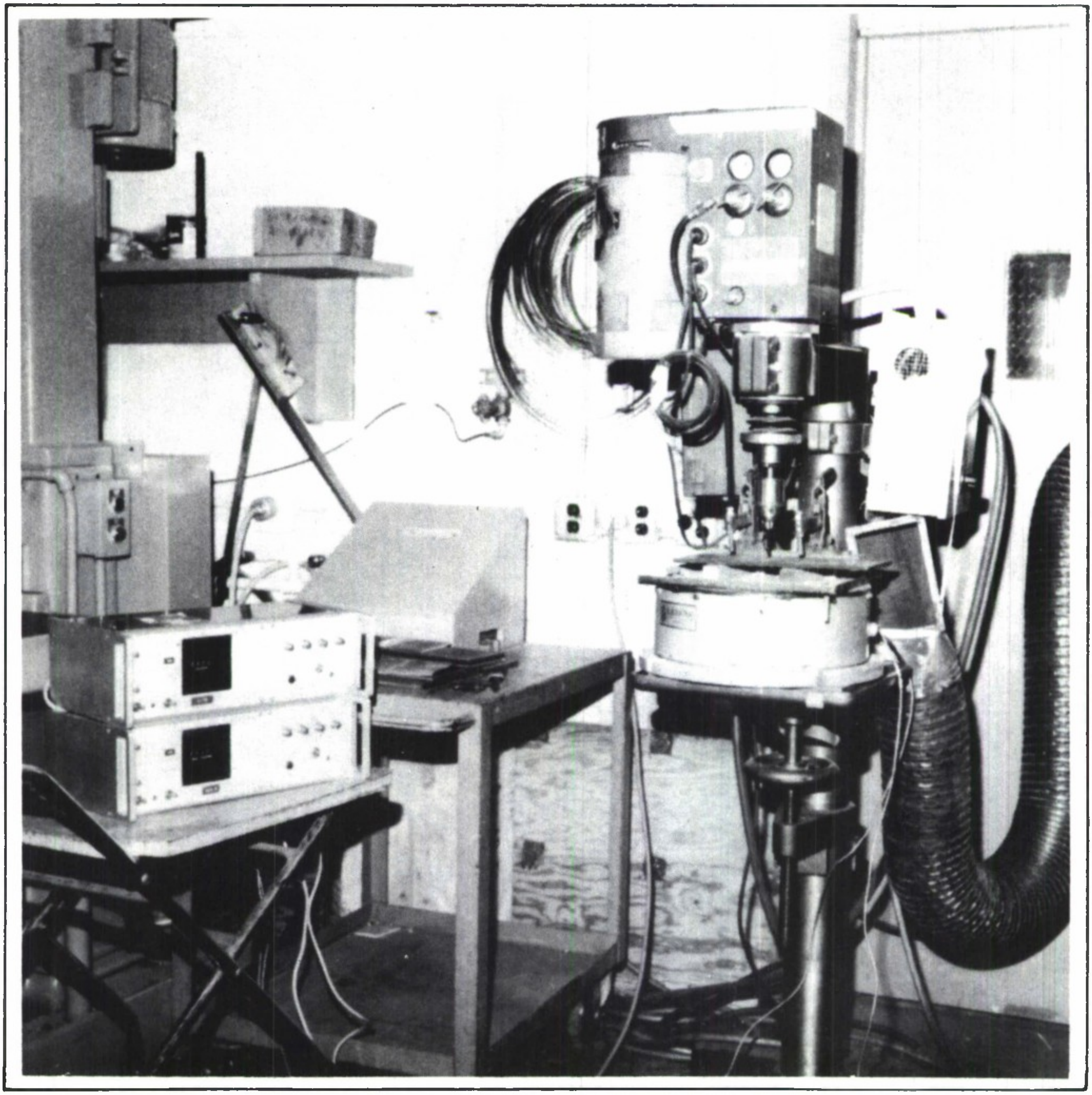


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Figure 5-6 Dumore Series 24 Drilling Machine with Dynamometer and Thrust/Torque Indicators

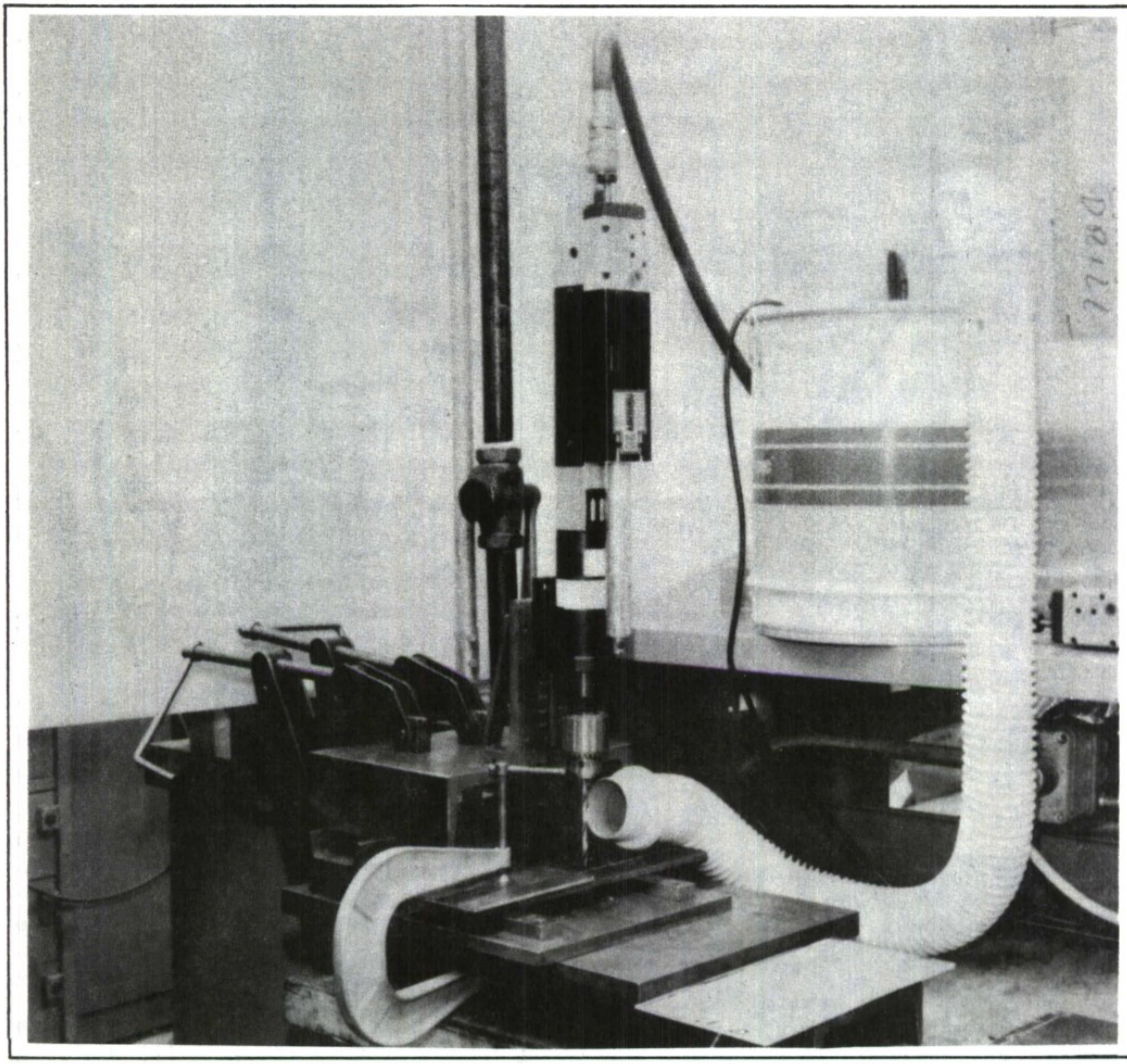

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Figure 5-7 Gardner-Denver Portable Drilling Machine

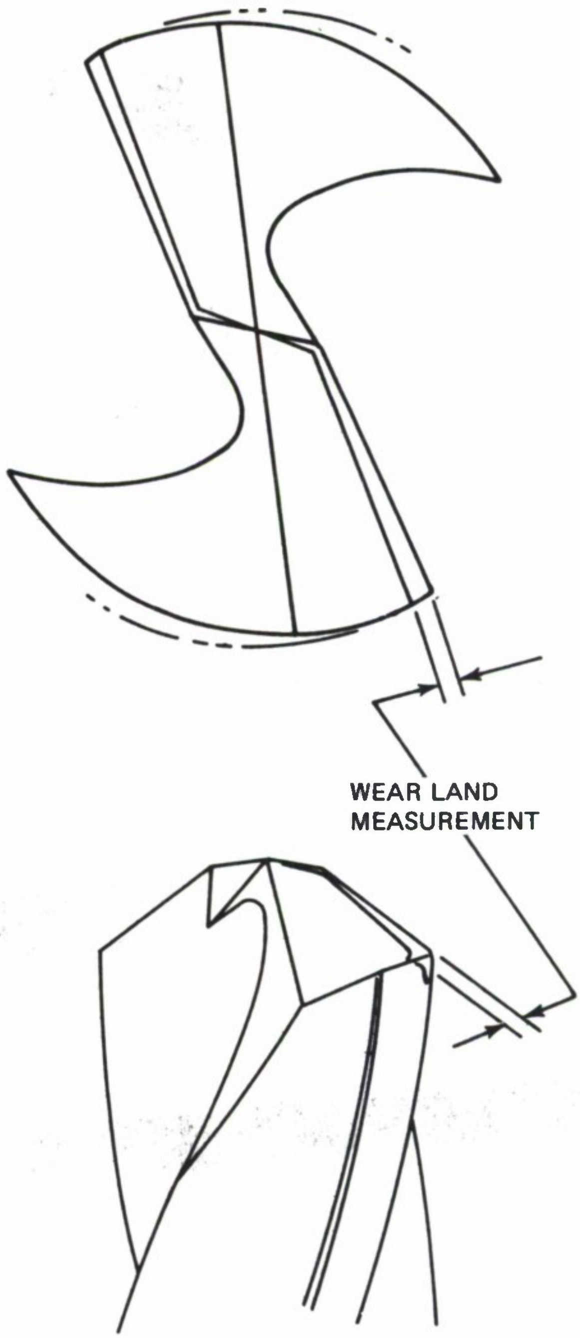

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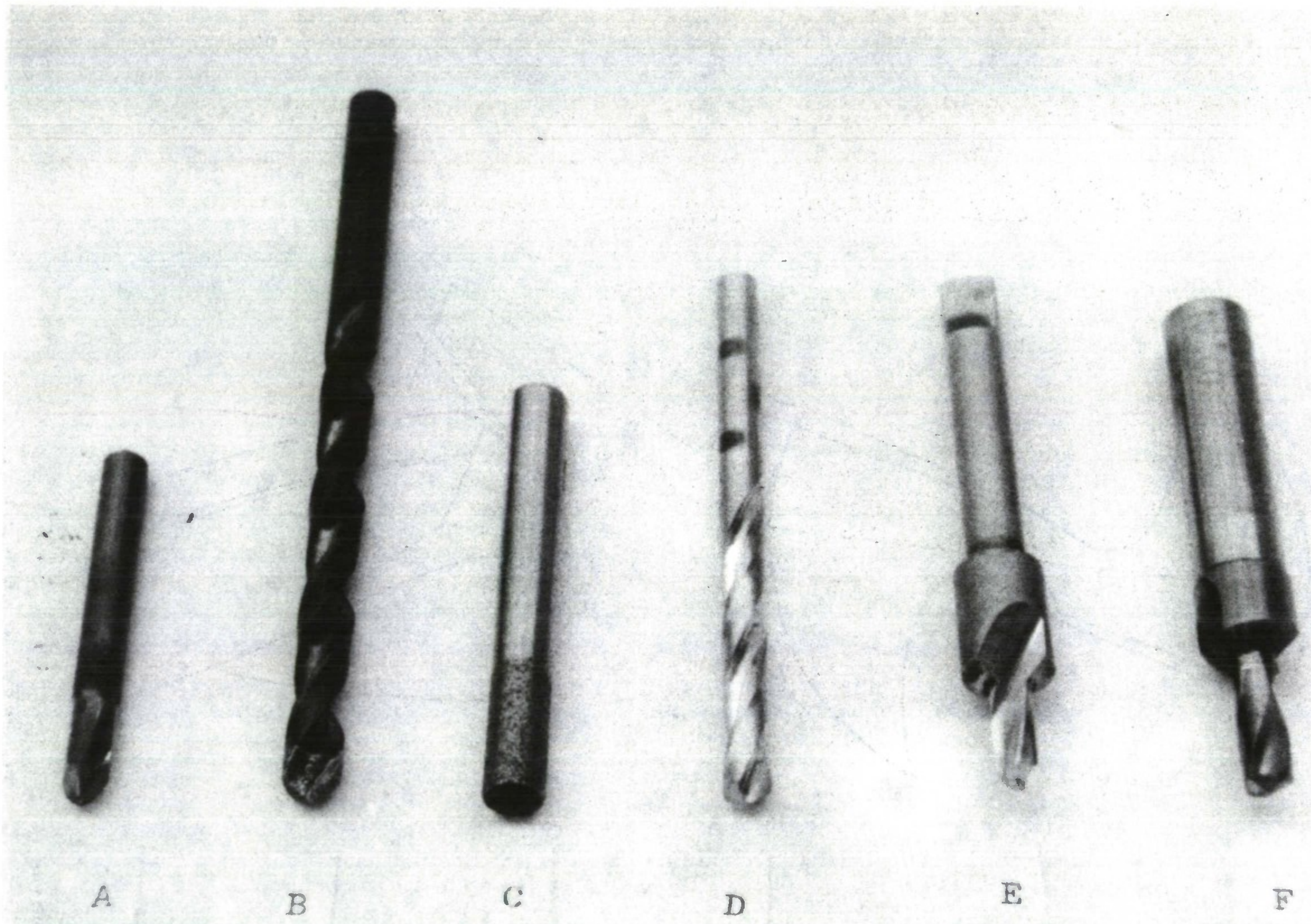
Figure 5-8 Location for Wear Land Measurement



A MEGADIAMOND (DIAMOND-COMPACTED, INSERTED)

B LUNZER, PLATED (DIAMOND, 80-100 GRIT)

C LUNZER, DIAMOND ELECTROFORMED

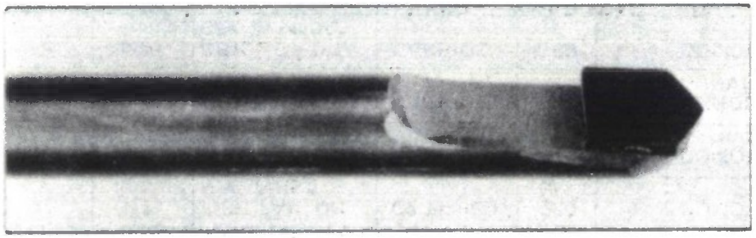
D ROTA-KOTE, CARBIDE DRILL (IMPINGED WITH DIAMONDS)

E ROTA-KOTE, HSS DRILL/ COUNTERSINK (IMPINGED WITH DIAMONDS)

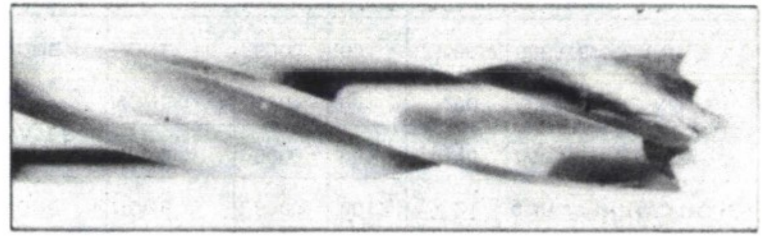
F ROTA-KOTE, CARBIDE DRILL/ COUNTERSINK (IMPINGED WITH DIAMONDS)

2566-032W

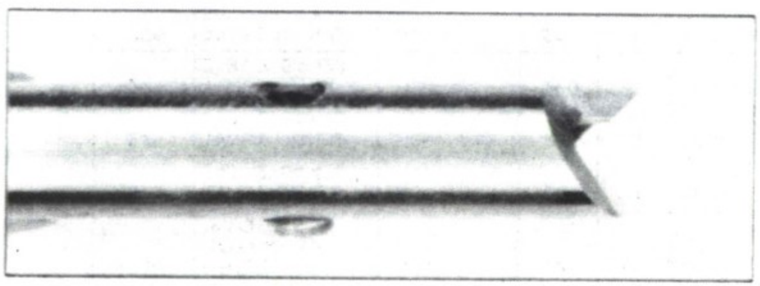
Figure 5-9 Alternate Drills for Supplemental Drilling Tests



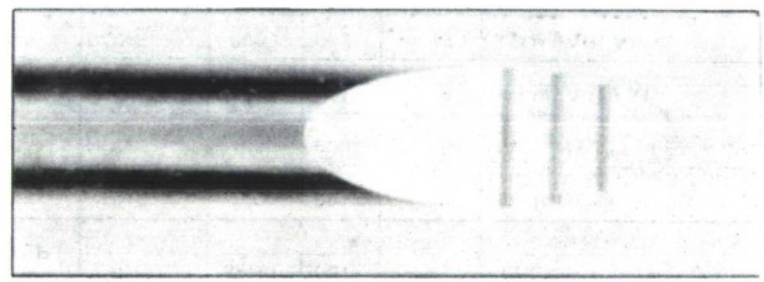
a. 3/16-Inch-Diameter Megadiamond Spade Drill (3x Mag)



b. 1/4-Inch-Diameter, Carbide Fish-Tail Drill (3x Mag)



c. 1/4-Inch Diameter, High-Speed Steel (Hss), Counterbore Drill (3x Mag)



d. 1/4-Inch-Diameter, Carbide Slant Drill (3x Mag)

1831-119B

Figure 5-10 Alternate Drill Configurations for Supplemental Drilling Tests

TEST		CUTTING TOOL										
MAT'L	THICK., IN.	TYPE DESCRIPTION	MAT'L	DIA., IN.	TEST NO.	EQUIP.	COOLANT	BACK-UP	SPEED, RPM	FEED, IPR	NUMBER OF HOLES	RESULTS/REMARKS
GR/EP	.300	DRILL ROTAKOTE	HSS	.125	2	DUMORE	DRY	NONE	6000	.001	6	WORN CUTTING EDGE
	.300	DRILL ROTAKOTE	CARBIDE	.1B7	3	DUMORE	DRY	NONE	6000	.001	300	HEAVY BREAKOUT
	.300	DRILL ROTAKOTE (SAME AS 2)	HSS	.125	16	DUMORE	HE2 & WATER	NONE	6000	.001	10	VERY BAD BREAKOUT
	.275	TWIST DRILL 3491-2754-423	HSS	.250	22	DUMORE	NONE	NONE	1000	.001	0	MACHINE STALLED – 115 # THRUST, B0 IN.-LB TORQUE
	.275	TWIST DRILL 3491-2754-423	HSS	.250	23	DUMORE	NONE	NONE	1000	.003	0	MACHINE STALLED – 105 #
	.275	TWIST DRILL 3491-2754-423	HSS	.250	24	DUMORE	NONE	NONE	3000	.001	B	.031 WEARLAND
	.275	TWIST DRILL 3491-2754-423	HSS	.250	25	DUMORE	NONE	NONE	3000	.003	14	.034 WEARLAND
	.275	TWIST DRILL 3491-2754-423	HSS	.250	26	DUMORE	NONE	NONE	6000	.003	6	ENTIRE LIP SURFACE WORN
	.275	TWIST DRILL 3483-2709-148	C2 TIPPED	.250	27	DUMORE	HE2 & WATER	NONE	6000	.001	60	.007 WEARLAND
	.270	TWIST DRILL 3483-2709-148	C2 TIPPED	.250	40	DUMORE	NONE	NONE	6000	.001	70	.006 WEARLAND
	.275	TWIST DRILL 3483-2709-148	C2 TIPPED	.250	32	GARDNER DENVER	NONE	NONE	10500	.001	B0	.011 WEARLAND
	.275	TWIST DRILL 3483-2709-148	C2 TIPPED	.250	36	DITTO	NONE/ VACUUM	NONE	10500	.001	1	TOO MUCH DUST/ SAFETY HAZARD
	.275	TWIST DRILL 3483-2709-148	C2 TIPPED	.250	29	DITTO	NONE	NONE	21000	.001	120	.008 WEARLAND
	1/4	FISH TAIL DR. N.Y. TWIST	C2 TIPPED	.250	9	DUMORE	NONE	NONE	6000	.001	21	BURN AROUND HOLES
	.275	DRILL OF DR/ CSK Z114104B	CARBIDE	.190	2B	DUMORE	HE2 & WATER	NONE	6000	.001	140	.006 WEARLAND
	.275	DRILL OF DR/ CSK Z114104B	CARBIDE	.190	30	GARDENER DENVER	NONE	NONE	21000	.001	290	.006 WEARLAND
	.270	DRILL OF DR/ CSK Z114104A	CARBIDE	.188	41	DUMORE	NONE	NONE	6000	.001	150	.006 WEARLAND
	.275	SPADE (SLANT) DRILL	CARBIDE	.250	38	GARDNER DENVER	NONE	NONE	21000	.0005	0	DRILL TIP CHIPPED
	5/16	VALERON SPADE DRILL	MEGA-DIAMOND	.190	1	DUMORE	NONE	NONE	6000	.001	0	CARBIDE SHANK BROKE
	.498	VALERON SPADE DRILL	MEGA-DIAMOND	.1B7	88	DUMORE	NONE	NONE	4500	.001	264	MEGADIAMOND CHIP FAILED; HOLES TAPERED
	.270	VALERON IN-SERTED DRILL	MEGA-DIAMOND	.2055	B9	DUMORE	NONE	NONE	2500 & 4500	.001	1000	CARBIDE TOOL SHANK FAILED; 0.004 WEARLAND HOLES TAPERED

2566-033W
(1/3)

Figure 5-11 Supplemental Drill Test Summary (Sheet 1 of 3)

TEST		CUTTING TOOL										
MAT'L	THICK., IN.	TYPE DESCRIPTION	MAT'L	DIA., IN.	TEST NO.	EQUIP.	COOLANT	BACK-UP	SPEED, RPM	FEED, IPR	NUMBER OF HOLES	RESULTS/REMARKS
	.270	MEGADIAMOND INSERTED DRILL TEST #1 REWORKED	MEGA-DIAMOND	.190	42	GARDNER DENVER	NONE	NONE	21000	.001	0	PANEL VIBRATED – TIP CHIPPED
	.295	CORE DR. – ABRASIVE TECH.	BORAZON	.253	47	UMT-3	WATER	POLY-URETHANE FOAM	4000	.001	67	FLUID CHUCK LEAK CAUSED PREMATURE WEAR
GR/EP WITH PEEL PLY	.275	LUNZER TWIST DRILL HSS	DIAMOND PLATED 80-100 GRIT	.250	4	DUMORE	DRY	NONE	6000	.001	60	CUTTING EDGE WORN
	.275	STARLITE TWIST DRILL HSS	DIAMOND PLATED 220 GRIT	.250	5	DUMORE	DRY	NONE	6000	.001	15	CUTTING EDGE WORN
	.275	STARLITE TWIST DRILL HSS	DIAMOND PLATED 100-120 GRIT	.250	6	DUMORE	DRY	NONE	6000	.001	6	PLATING PEELED OFF
	.275	TWIST DRILL 2483-2709-148	C2 TIPPED	.250	7	DUMORE	DRY	NONE	6000	.001	120	≈ .008 WEARLAND-GOOD HOLES
	.310	RADIAL LIP POINT DRILL	CARBIDE MICRO-GRAIN	.258	8	DUMORE	DRY	NONE	6000	.001	61	≈ .010 WEARLAND
	.250	DRILL/C'SINK ROTAKOTE	HSS	.190	21	DUMORE	DRY	NONE	6000	.001	10	BAD BREAKOUT, CHIPS BURNED
	.330	CORE DRILL LUNZER	ELECTRO-FORMED DIAMOND 80-100 GRIT	.251	67	BRANSON UMT 3	WATER	POLY-URETHANE FOAM	4000	.001	235	EXCESSIVE CORE HANGUP, TEST CONCLUDED
GR/EP + FG/EP	.330	TWIST DRILL 3483-2709-148	C2 TIPPED	.250	43	DUMORE	DRY	NONE	6000	.001	50	.006 WEARLAND
	.325	CORE DRILL ABRASIVE TECH	DIAMOND PLATED 80-100 GRIT	.196	45	UMT-3	WATER	POLY-URETHANE FOAM	4000	.001	26	DAMAGE BY LOW WATER PRESSURE
	.330	CORE DRILL ABRASIVE TECH	DIAMOND PLATED 80-100 GRIT	.200	46	UMT-3	WATER	POLY-URETHANE FOAM, FG/EP & PLY-WOOD	4000	.001	300	FG/EP AND PLYWOOD NOT GOOD FOR BACKUP
GR/EP + KEVLAR/EP	.275	OPPOSED HELIX DRILL PEN ASSOC	CARBIDE	.250	71	CLECO HD. DR.	DRY	NONE	150 TO 400	HAND	40	≈ .001 WEARLAND POOR HOLE QUALITY
	.280	2 FLUTE C'BORE DRILL JANCY	HSS	1/4	44	DUMORE	DRY	NONE	3000	.001	3	POOR HOLE QUALITY
	.275	FISH TAIL DR. N.Y. TWIST	C2 TIPPED	1/4	13	DUMORE	DRY	NONE	6000	.001	11	POOR HOLE QUALITY
KEVLAR/EPOXY	.118	TWIST DR 391-2754-361	HSS	.125	10	DUMORE	NONE	NONE	6000	.001	40	POOR HOLE QUALITY
	.118	TWIST DR 391-2754-423	HSS	.250	11	DUMORE	NONE	NONE	6000	.001	14	HEAVY BREAKOUT

2566-033W
(2/3)

Figure 5-11 Supplemental Drill Test Summary (Sheet 2 of 3)

TEST		CUTTING TOOL										
MAT'L	THICK., IN.	TYPE DESCRIPTION	MAT'L	DIA., IN.	TEST NO.	EQUIP.	COOLANT	BACK-UP	SPEED, RPM	FEED, IPR	NUMBER OF HOLES	RESULTS/REMARKS
KEVLAR/ EPOXY (CONT)	.118	JANCY 2 FLUTE C'BORE DR	HSS	.250	14	DUMORE	NONE	NONE	6000	.001	65	APPROX 40 GOOD HOLES
	.118	SAME AS #14 LESS PILOT	HSS	.250	15	DUMORE	NONE	NONE	3000	.001	30	HEAVY BREAKOUT AFTER 9
	.120	GAC DESIGN FISH TAIL	HSS	.250	31	GARDNER DENVER	NONE	NONE	21000	.0005 .0003	1 EA.	POOR HOLE QUALITY
	.118	TWIST DR 3483-2709-148	C2 TIPPED	.250	17	DUMORE	NONE	NONE	6000	.001	5	POOR HOLE QUALITY
	.118	FISH TAIL DR. N.Y. TWIST	C2 TIPPED	.125	12	DUMORE	NONE	NONE	6000	.001	20	HEAVY BREAKOUT
	.118	FISH TAIL DR. N.Y. TWIST	C2 TIPPED	.250	18	DUMORE	NONE	NONE	6000	.001	5	POOR HOLE QUALITY
	.118	FISH TAIL DR. N.Y. TWIST	C2 TIPPED	.250	19	DUMORE	NONE	NONE	3000	.002	5	POOR HOLE QUALITY
	.118	SPADE (SLANT) DR.	CARBIDE	.250	20	DUMORE	NONE	NONE	6000	.001	6	EXCESSIVE STARRING
	.118	SPADE (SLANT) DRILL	CARBIDE	.250	37	GARDNER DENVER	NONE	NONE	21000	.001/ .0005	1 EA.	DRILL TIP CHIPPED } NO BUSHING USED
	.118	SPADE (SLANT) DRILL	CARBIDE	.187	39	GARDNER DENVER	NONE	NONE	21000	.0005 .00025	1 EA.	DRILL TIP CHIPPED } NO BUSHING USED
	.118	SPADE (SLANT) DRILL	CARBIDE	.250	69	GARDNER DENVER	NONE	NONE	21000	.0002	1	USED ST 2662 BUSHING SOME BREAKOUT
	.118	SPADE (SLANT) DRILL	CARBIDE	.250	69A	DUMORE	NONE	NONE	6000	.0008	3	BAD BREAKOUT
	.118	OPPOSED HELIX DRILL PEN ASSOC	CARBIDE	.250	70	DUMORE AND CLECO DRILL	NONE	NONE	6000 400 TO 4500	.001 HAND	17	POOR QUALITY HOLES
	.306	SPADE (SLANT) DRILL	CARBIDE	.250	(1)	CLECO DRILL	NONE	NONE	25000	OFF-HAND	300	CLEAN HOLES, NO BUSHING USED

(1) SEE REFERENCE 8

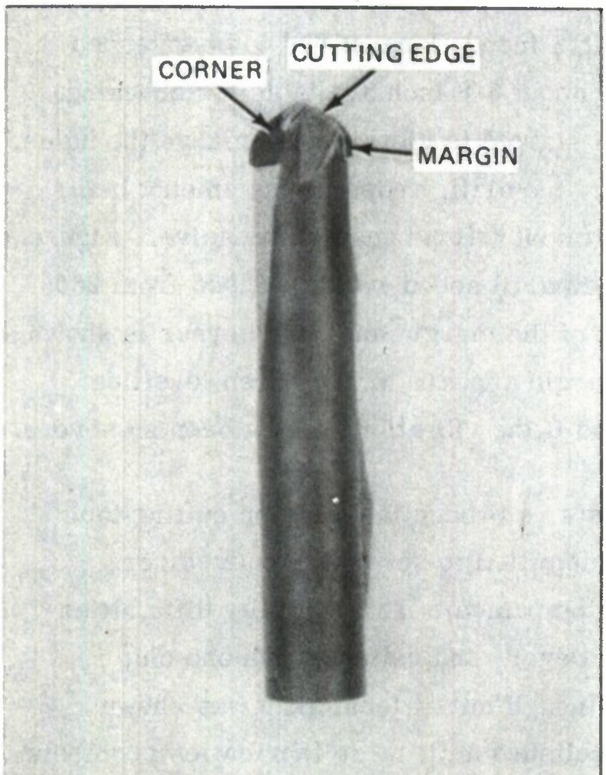
2566-033W
(3/3)

Figure 5-11 Supplemental Drill Test Summary (Sheet 3 of 3)

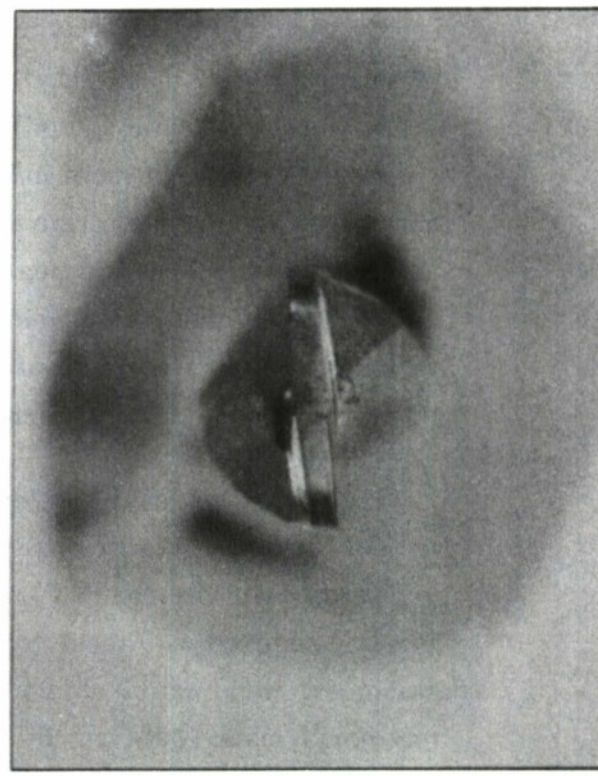
- Inserted Chip, Compacted Diamond - In an attempt to establish new cutting tool materials having better abrasion resistance and dimensional stability, a joint effort with several diamond tool manufacturers was conducted to evaluate diamond-compacted, inserted-tooth cutting tools. The Valeron Corporation fabricated and tested a compacted-diamond, inserted-chip (megadiamond), 0.2055-in.-diameter drill with a spade-type point (Figure 5-12). This drill was sent to Grumman for further testing after 400 holes had been drilled with it. Six-hundred additional holes were drilled at Grumman in 0.270-inch-thick graphite/epoxy panels with peel ply. No coolant or backup was used. The test was terminated at this point (after 1000 holes had been drilled). The drill was made 1-1/8 inches long; it had to be extended 1/2 inch from the chuck, leaving only about 5/8 inch available for chucking. After drilling the 700th hole, the drill started to vibrate and enlarge the holes. A piece then broke off the shank-end of the drill, reducing the amount being chucked. The test was terminated after vibration became excessive. Figure 5-13a shows that thrust decreased when drill speed was increased from 2500 to 4500 rpm. Wear land development of the margin and drill corner is shown in Figure 5-13b. Wear land of the margin appears to have been levelling off; more holes could have been drilled if the vibration had not been so severe.

  Based upon the results of these tests, a production-version cutting tool was designed (see Figure 5-14) and submitted to several manufacturers for fabrication (Valeron and Lunzer Companies). Producibility difficulties were encountered with these tools, however, and reliable diamond chip attachment could not be obtained. Although initial feasibility was shown final performance data cannot be established until these fabrication problems are resolved.

- Jancy 2-Flute Counterbore - This drill was evaluated in 0.118-inch-thick Kevlar/epoxy using a Dumore drill machine at 6000 rpm and 0.001 ipr feed. No coolant or back-up was used. The panel was clamped over two 1-inch parallels spaced 3.75 inches apart. The first 10 holes were made using the No. 40 (0.198-inch) pilot drill which hindered clean cutting. Kevlar fibers packed into the pilot drill opening preventing proper chip

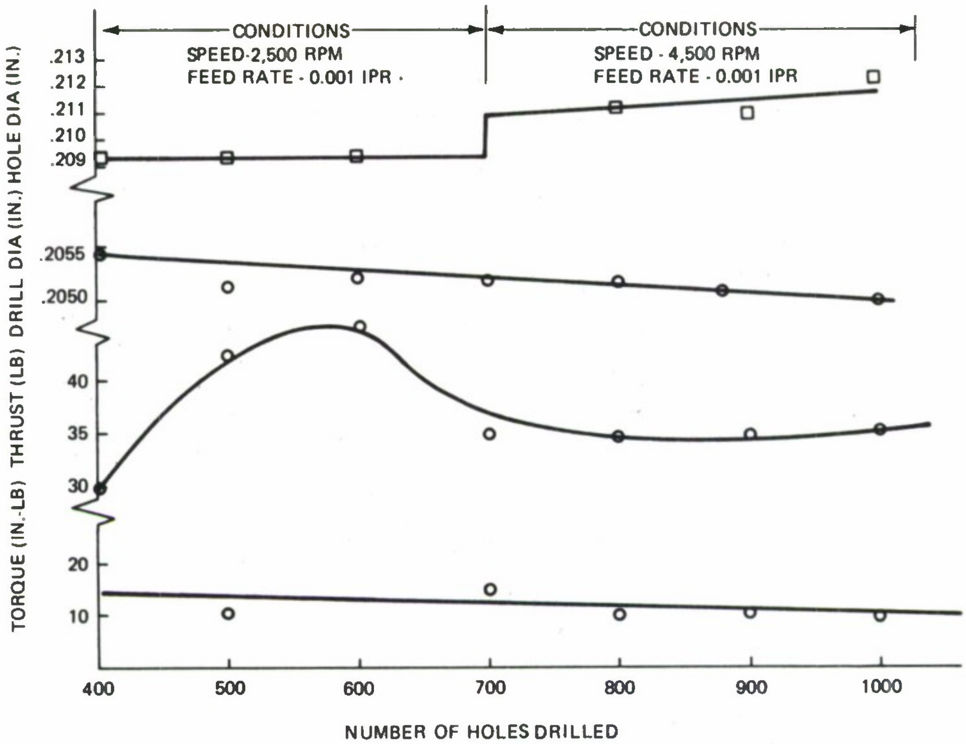


a. Side View (3x Mag)


b. End View (8x Mag)

2566-034W

Figure 5-12 Valeron 0.2055-Inch-Diameter, Megadiamond Drill (118° Point)



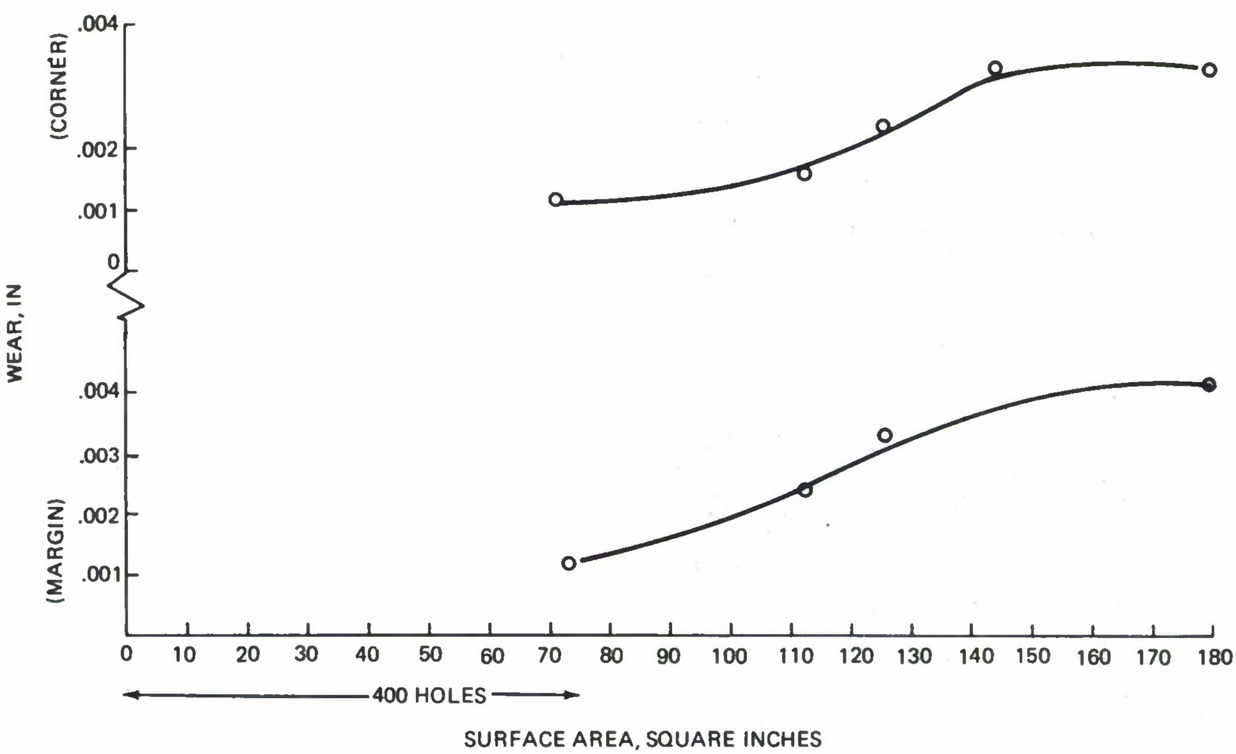


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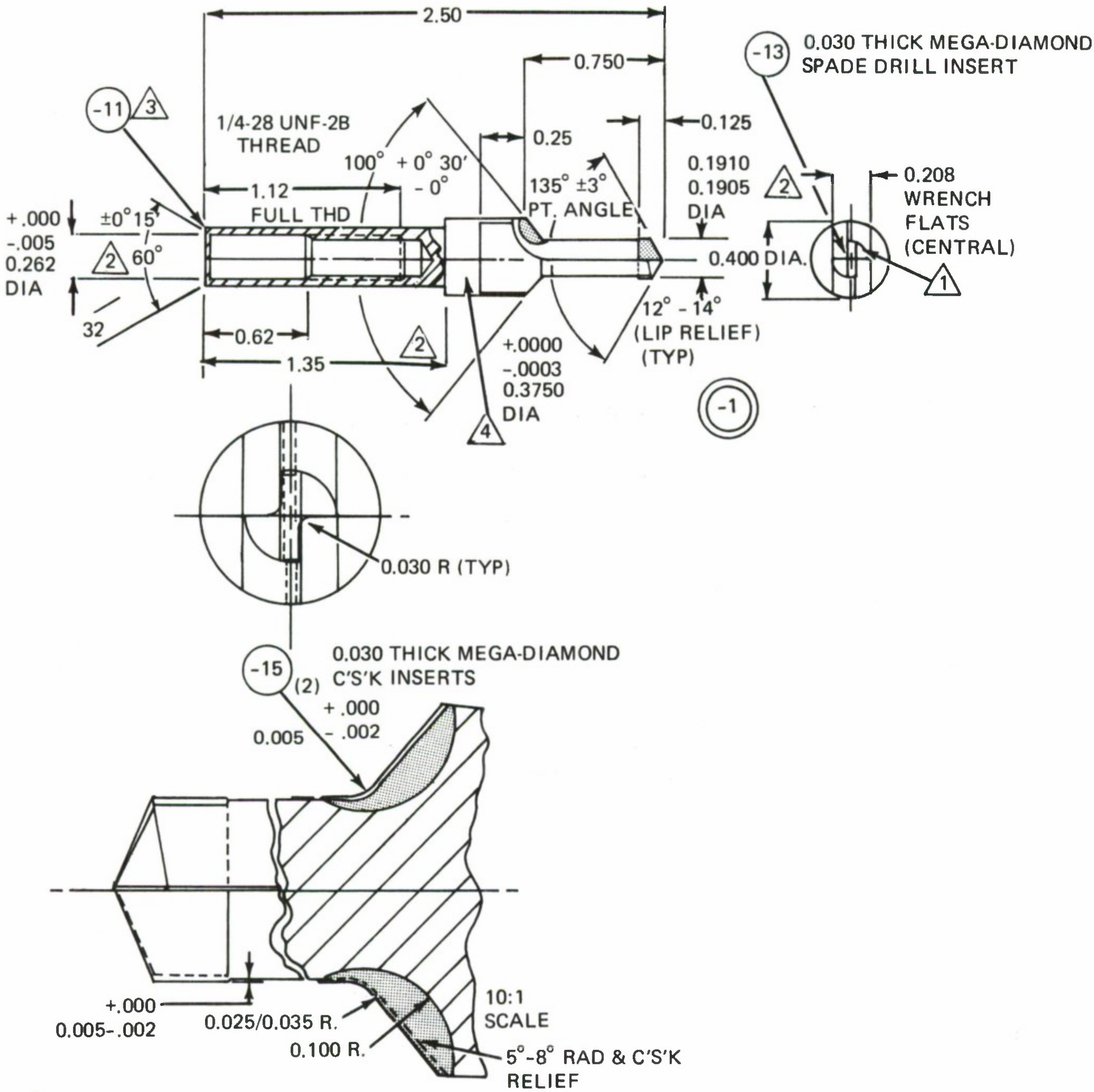
Figure 5-13 Performance of Valeron Megadiamond Inserted Drill (0.2055-In.Diameter)



1 12° CLEARANCE AFTER PRIMARY RELIEF

2 CONCENTRIC WITHIN 0.0005 T.I.V.

3 -11 TO BE HEAT TREATED TO 160 KSI; PRE-HARDENED STOCK MAY BE USED.

4 IDENTIFY TOOL NO.

1831-123B

Figure 5-14 Spade Drill/Countersink Combination Tool

removal and making clean cutting difficult. After the pilot drill was removed acceptable quality holes were achieved in spite of the fact that fibers packed into the pilot drill hole. Slight starring (exit delamination) was observed by the 15th hole. By the 19th hole, the Kevlar core remained with the parent material; a few strands were not cut. However, to Hole No. 50, the quality was considered acceptable.

Of the drills tested in Kevlar/epoxy, this drill produced the best results for the test conditions used. The following procedure should extend drill life and hole quality:

1. Clean the drill of epoxy and fiber residual after approximately every 5 holes. Clean drills cut better.

2. Kevlar does not support the cutting tool during cutting; therefore, bushings and rigid setups are recommended.

Tests also showed the following drills to be ineffective or unacceptable:

- Diamond-Plated Drill Tips - The diamond platings applied to HSS drill tips breakoff or wear out rapidly, diminishing the inherent potential of diamond tools. Breakout with diamond-coated drills is also more severe than that encountered with conventional chisel-point drills.

- Diamond-Impinged Drills - Testing of both HSS and solid carbide drills which had been Rota-Koted (mechanical process by which diamond particles are impinged onto the surface) did not alter performance on life over that of the uncoated drills.

- Carbide-Tipped Fishtail Drills - Five drills were evaluated with graphite/epoxy, graphite/epoxy plus Kevlar/epoxy and Kevlar/epoxy as follows:
  - 1/4-inch dia. in graphite/epoxy at 6000 rpm on 0.001 in.; 21 holes
  - 1/4-inch dia. in graphite/epoxy plus Kevlar/epoxy at 6000 rpm on 0.001 ips; 11 holes
  - 1/8-inch dia. in Kevlar/epoxy at 6000 rpm on 0.001 in.; 20 holes
  - 1/4-inch dia. in Kevlar/epoxy at 6000 rpm on 0.001 in.; 5 holes
  - 1/4-inch dia. in Kevlar/epoxy at 3000 rpm at 0.002 in.; 5 holes

The first two holes in graphite/epoxy were of acceptable quality; for the balance, increasingly unacceptable breakout developed. Unacceptable breakout or hole quality occurred from the beginning in the remaining four tests, resulting in rapid termination of the tests. This drill point configuration is not recommended for the composites tested based on the evaluations made.

- Jancy 2-Flute Counterbore - This drill was evaluated with graphite/epoxy plus Kevlar/epoxy. A speed of 3000 rpm was used with a 0.001 ipr feed for a material thickness of 0.280 inch. Only three holes were drilled, since very poor quality was obtained. Sharp cutting edges are required for Kevlar/epoxy. The HSS drill cannot maintain a sharp edge after cutting through graphite/epoxy. This drill is not recommended for this material combination.

- Borazon Core Drill- A nickel-plated (0.010-inch thick), Borazon core drill was evaluated with 0.321-inch-thick graphite/epoxy. Rigid polyurethane foam was used as backup material for this test. The first twenty holes were drilled cleanly and easily without exit delamination. From the 21st to the 67th hole, exit delamination became progressively worse. When drilling the 44th hole, a very noticeable increase in thrust and drilling time was observed. At Hole No. 63, drilling time per hole increased to 60 seconds.

- Diamond Core Drills - Diamond-plated core drills of 0.196-inch-diameter were used to drill 0.325-inch-thick graphite/epoxy. Drilling parameters included 4000 rpm and 0.001 ipr feed. The material was backed up with polyurethane foam and coolant (water) was passed through the core drill. Results showed that 300 high-quality holes could be produced if a good backup material was used. However, these drilling parameters would not be as cost-effective as carbide drilling (longer penetration time).

- Carbide Slant Drills - Slant drills of 3/16- and 1/4-inch diameter were tested on 1/8-inch-thick Kevlar/epoxy at 21,000 rpm speed and feeds ranging from 0.00025 to 0.001 ipr. Testing was also conducted with and without a hand-held bushing jig. In all cases, chipping of the drill point occurred rapidly; as a result, very few holes were drilled. It would appear that these drills should utilize a bushing which is integral with the portable drill to enable them to perform satisfactorily.

5.2.2 Carbide Drills and High Cutting Speed for Graphite/Epoxy

Baseline drilling tests were performed in 0.275-inch-thick graphite/epoxy using a Dumore drilling machine at 6000 rpm and 0.001 ipr feed. Both solid carbide (0.190-inch diameter) and carbide tipped (0.250-inch diameter) cutting tools were used. Using the 0.006-inch wear land development criteria, 60 holes (1080 linear feet) were obtained with the carbide-tipped drill and 140 holes (1915 linear feet) with the solid carbide drill as shown in Figures 5-15 and 5-16.

High cutting speed tests were conducted on a 21,000 rpm, portable, air-driven, Gardner Denver machine. Conditions used involved a constant 0.001-ipr feed, 0.190-inch-diameter solid carbide drills and 0.250-inch-diameter carbide-tipped drills. The results show that much greater tool life is attained at 21,000 rpm (Figures 5-17 and 5-18). For the 0.190-inch-diameter solid-carbide drill, 280 holes (3830 linear feet) were drilled; 80 holes or 1440 linear feet were obtained from the 0.250-inch-diameter carbide-tipped drill. Thus, by increasing speed from 6000 to 21,000 rpm, tool life was doubled. Results also show that the solid carbide drills outperformed carbide-tipped drills by over 2.5 to 1.

Further analysis shows that, when drilling graphite/epoxy, hole size tends to be less than the drill diameter as margin wears. When drilling metals, the reverse is observed; normal drill dimensions allow for this condition by placing tolerances on the minus side.

Drill point configurations used in carbide tools are shown in Figures 5-19 and 5-20. Solid carbide tools utilize 135° point angles while carbide-tipped tools have 118° point angles. Previous testing at Grumman (Reference 2) showed no difference in cutting performance between the two point angles.

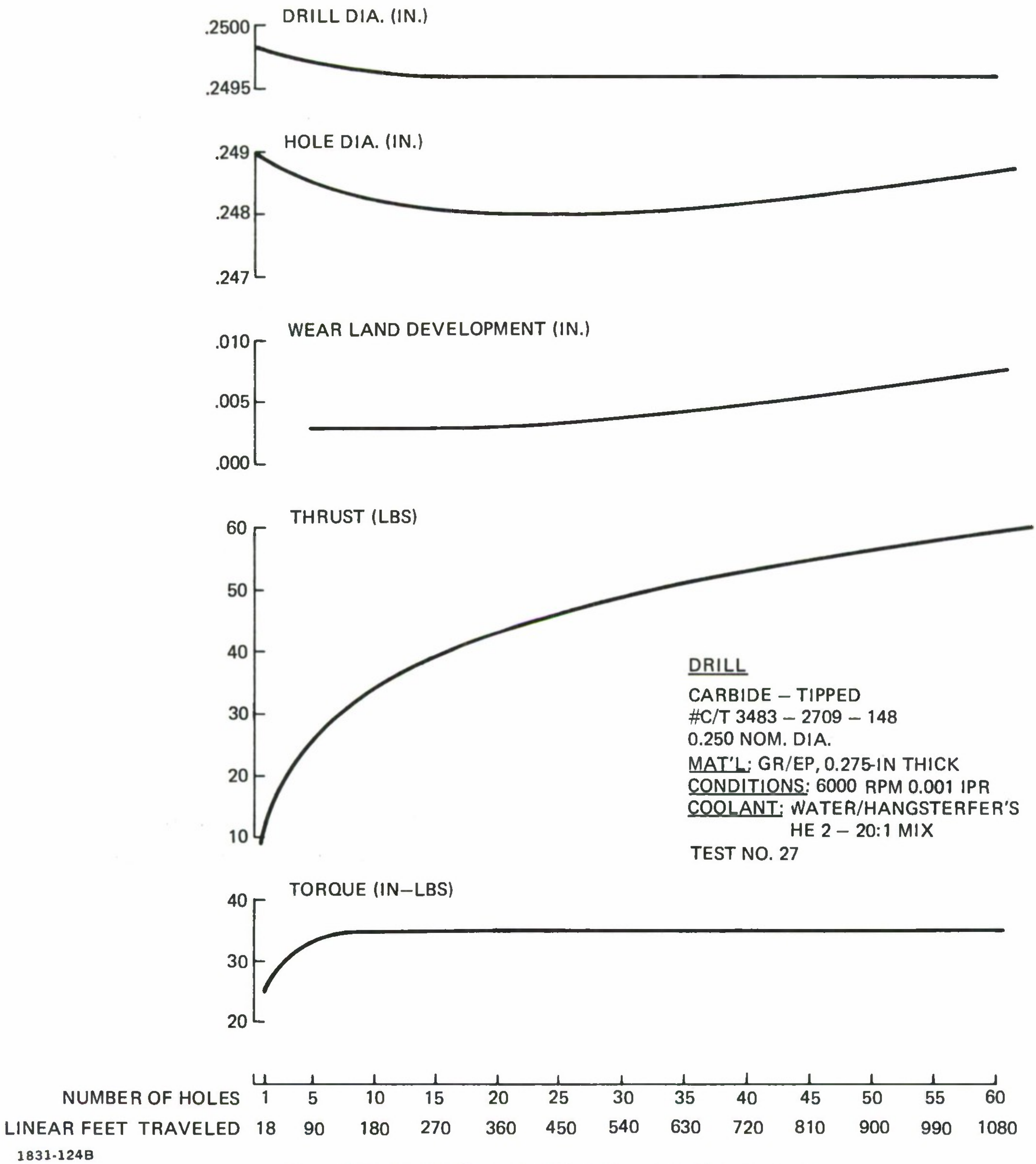


Figure 5-15 Carbide-Tipped Portable Drilling Data (With Coolant)

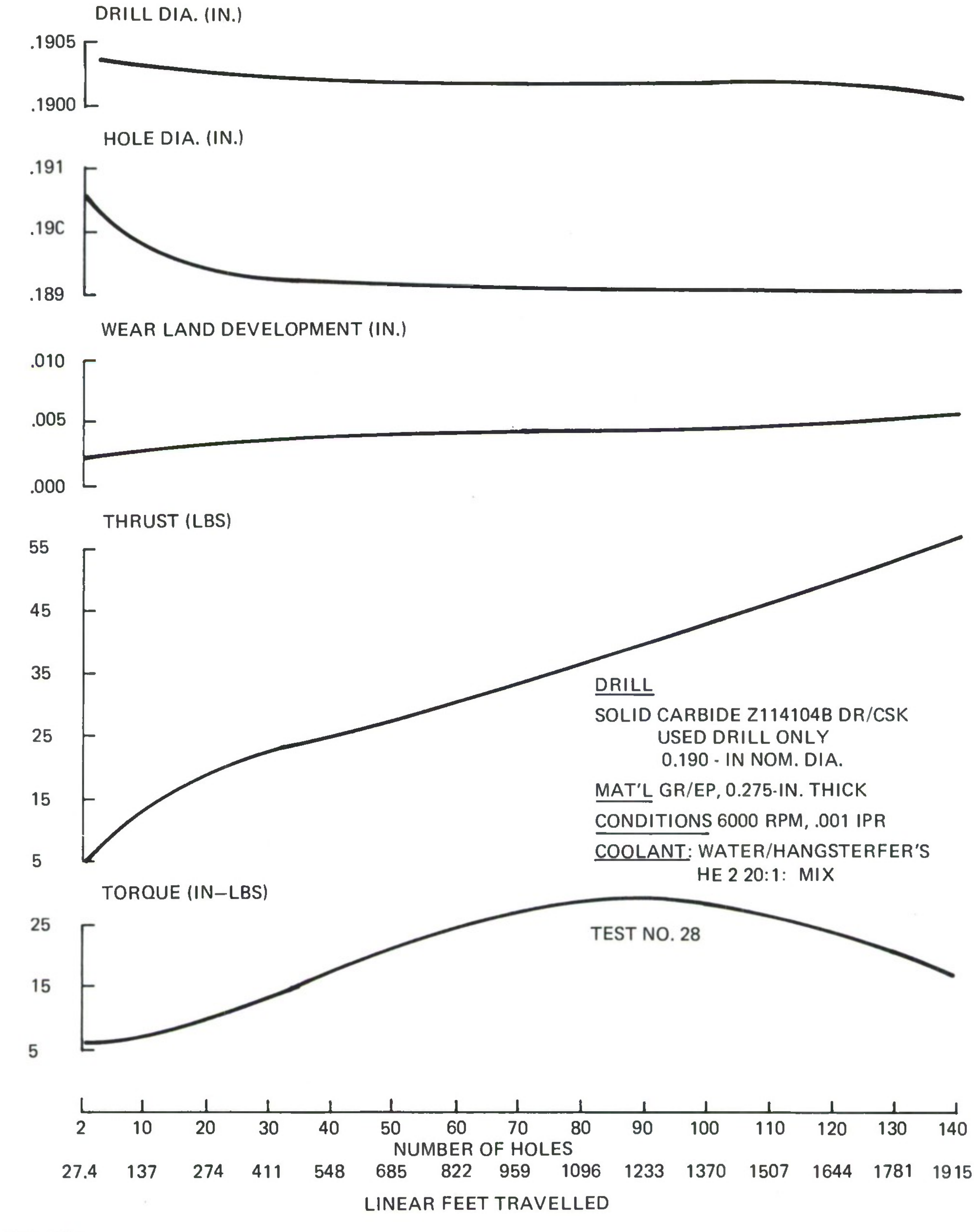


Figure 5-16 Solid-Carbide Portable Drilling Data (With Coolant)

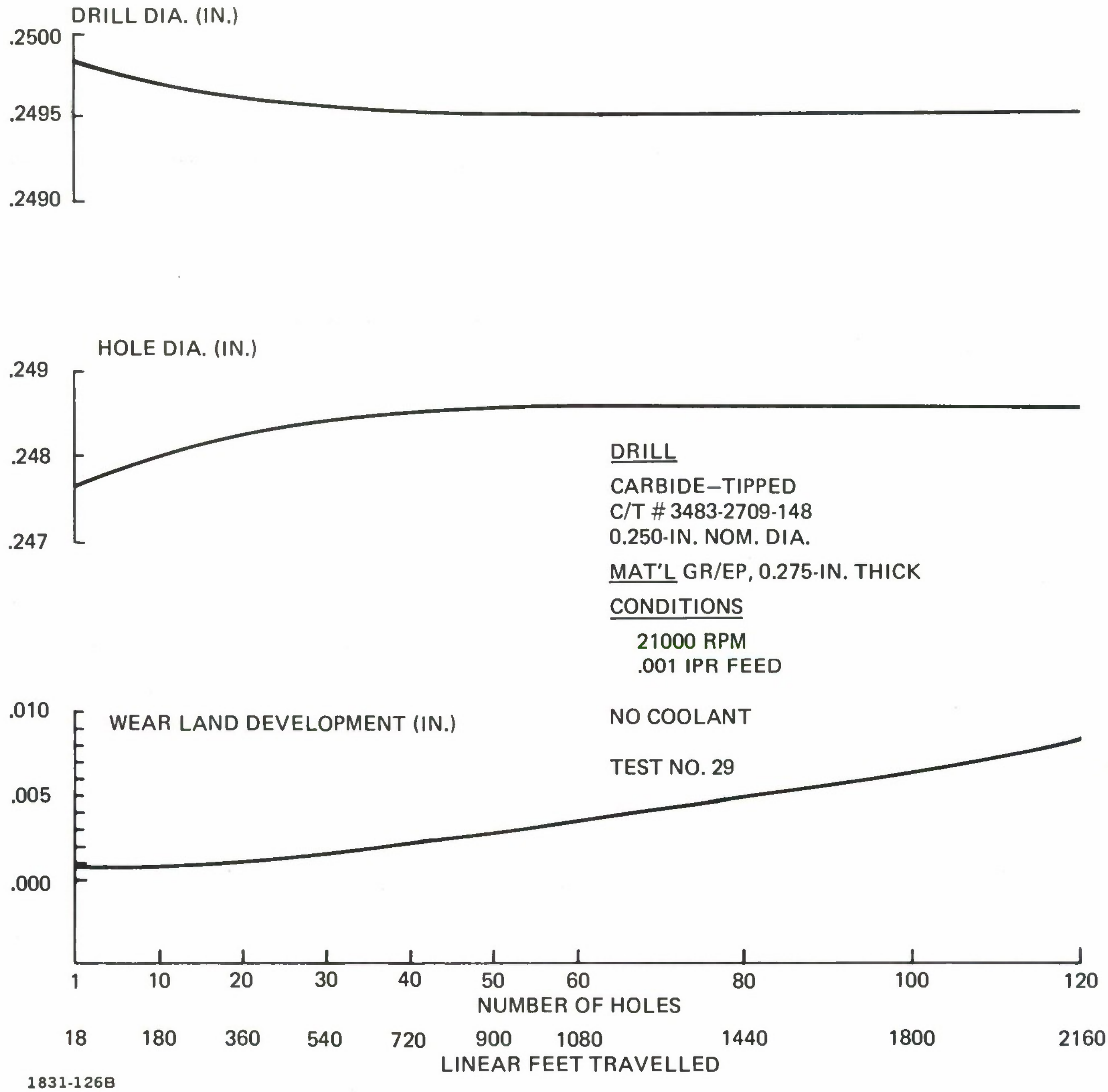


Figure 5-17 Carbide-Tipped Portable Drilling Data (Without Coolant at 21,000 RPM)

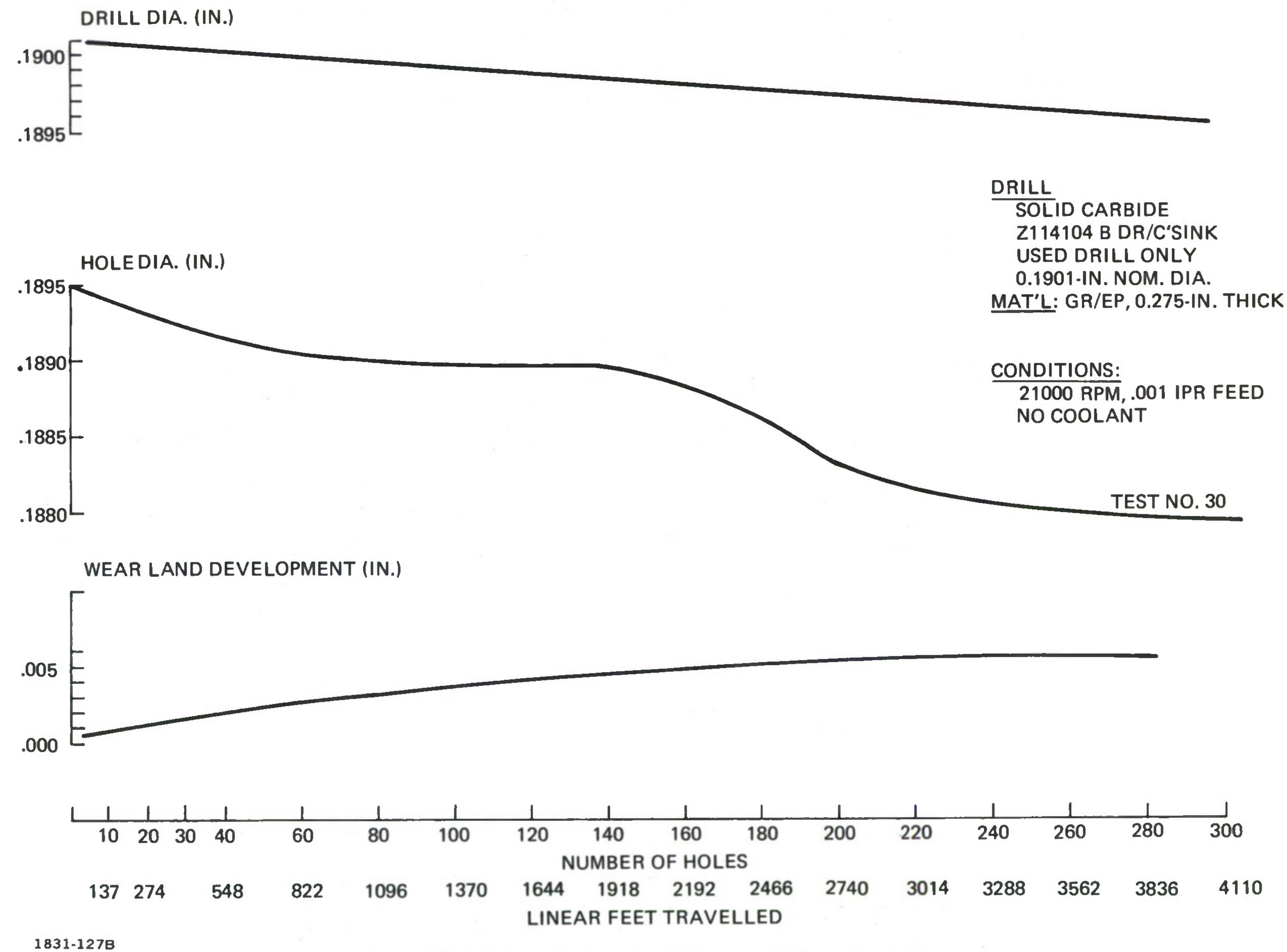
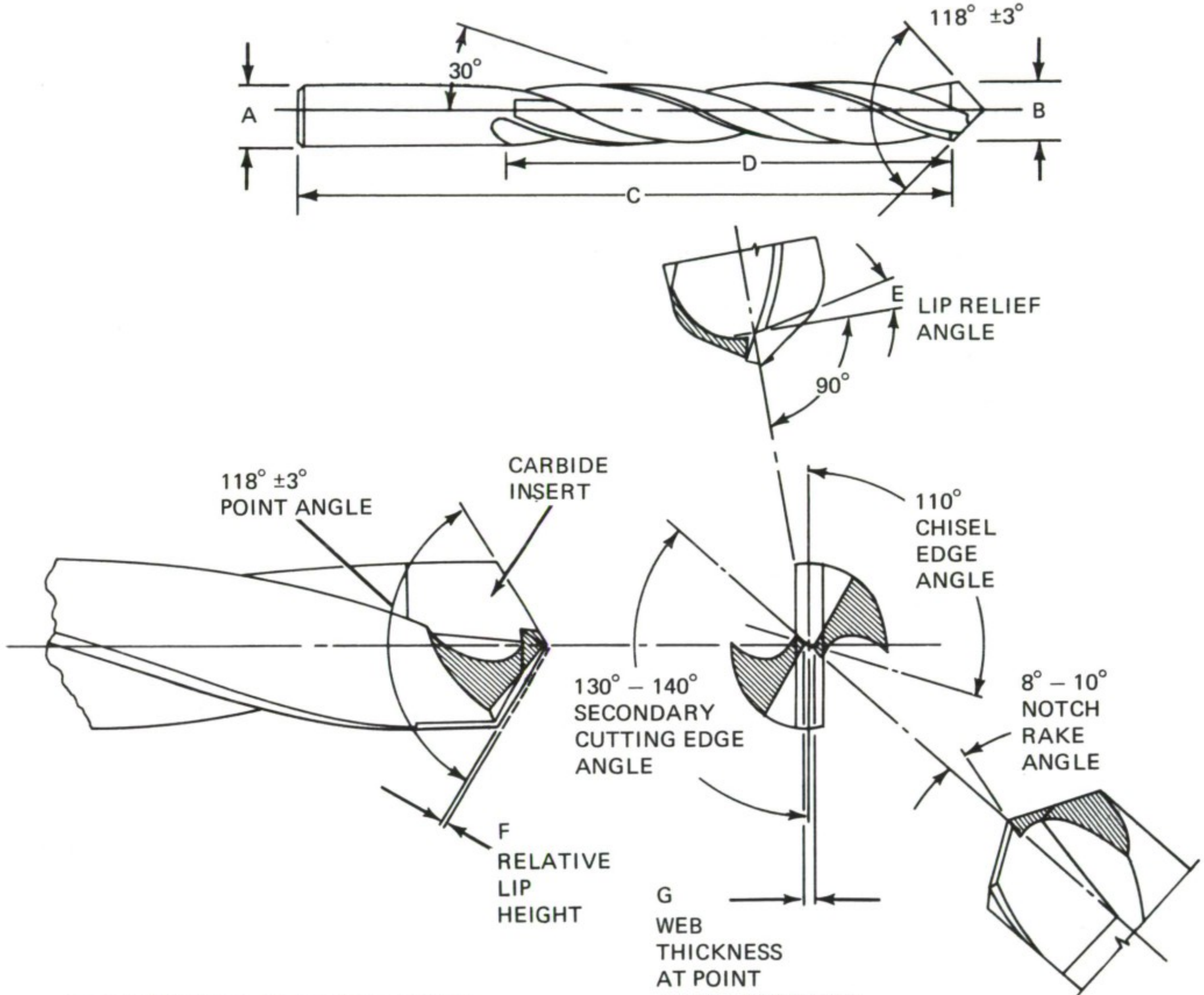


Figure 5-18 Solid-Carbide Portable Drilling Data (Without Coolant)



TOOL MATERIAL C2 OR C6 CARBIDE

A*	B*	C*	D*	E	F	G	GRUMMAN CODE NO.
1/4	.2500	4.00	2.75	10° – 16°	.003	.007/.010	CT 3483-2709-148

*DIMENSIONS AND TOLERANCES NOT SPECIFIED TO BE PER USAS B94.11-1967

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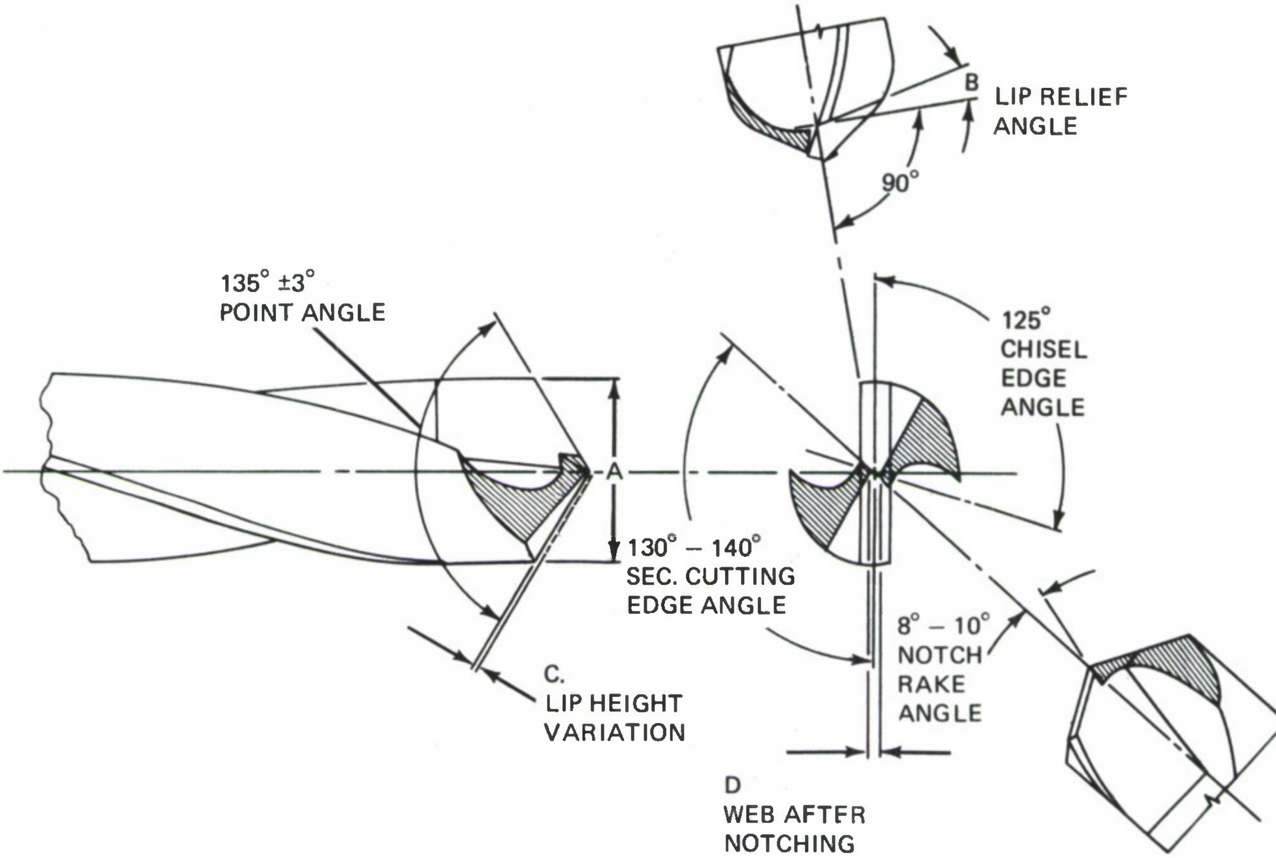
Figure 5-19 Carbide Tipped Twist Drill



CT GEOMETRIC FEATURE	VALUE	TOL.
SPLIT WEB CENTRALITY	.003	TIV
ALIGNMENT OF SPLIT	.002	TIV
HELIX ANGLE, DEG	20	±1
WEB TAPER, IN/IN.	.032	REF
DRILL BK TAPER, IN/IN.	$\frac{.0005}{.00010}$	
MARGIN WIDTH, IN.	.015	±.010 -.005

A	B	C	C	GRUMMAN CODE NO.
.2500	$14\ ^{+3°}_{-0°}$	.001	.005 .010	CSZ 114104 OR CSZ 114105

2566-038W

Figure 5-20 Solid Carbide Drill (Split Point)

5.3 TASK 3 - ASSEMBLY DRILLING

In general, aircraft structures are fabricated on the assembly floor. The experience gained in drilling composites on such hybrid structures as the B-1 horizontal stabilizer has produced a number of unique problems which are not incurred or accounted for by testing in a machining laboratory. The purpose of this task was to identify the impact of these factors on drilling costs and performance. Several typical assembly drilling considerations were used in this evaluation: composite drilling cutting forces; graphite/epoxy portable drilling; graphite-boron/epoxy hybrid drilling; portable honing; graphite hybrid transfer drilling to metal substructure; dry versus wet drilling; controlling exit delamination.

5.3.1 Composite Drilling Cutting Forces

The cutting forces associated with the required composite drilling operations determine the type of assembly or portable drilling equipment required. From the supplemental drilling test results, it can be seen that an axial thrust of approximately 55 pounds is achieved when drilling 3/16-inch-diameter holes in graphite/epoxy. For this reason, a portable tool with clamp-up capability is required to offset thrust loads. In addition, the portable equipment inherently yields a higher quality hole than off-hand drilling.

5.3.2 Graphite/Epoxy Assembly Drilling

A recognized, low-cost approach to conventional assembly drilling involves the use of Winslow-Spacematic portable drills (Figure 5-21). These units normally provide good clamping force and power feed. The clamp-up force, however, is exerted by a collet which is placed through a previously drilled hole into the substructure. For composite drilling operations, the collet would broach or crush the composite structure and is, therefore, unacceptable. This problem was solved by modifying the M-62 Winslow-Spacematic drill units with vacuum pads (Figure 5-22) to permit power feeding of the drill unit in place of a pullup type of colleted mandrel.

Portable power equipment provides the rigidity and feed control (lacking in offhand equipment) that is necessary to extend tool life and to provide close-tolerance, high-quality holes. To take advantage of the higher speeds recommended for drilling graphite/epoxy, portable power equipment is also required. Rigid fixturing is necessary to maximize the benefits inherent in using portable equipment.

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Figure 5-21 Winslow Spacematic Air-Powered Drill Unit (Model J-200)

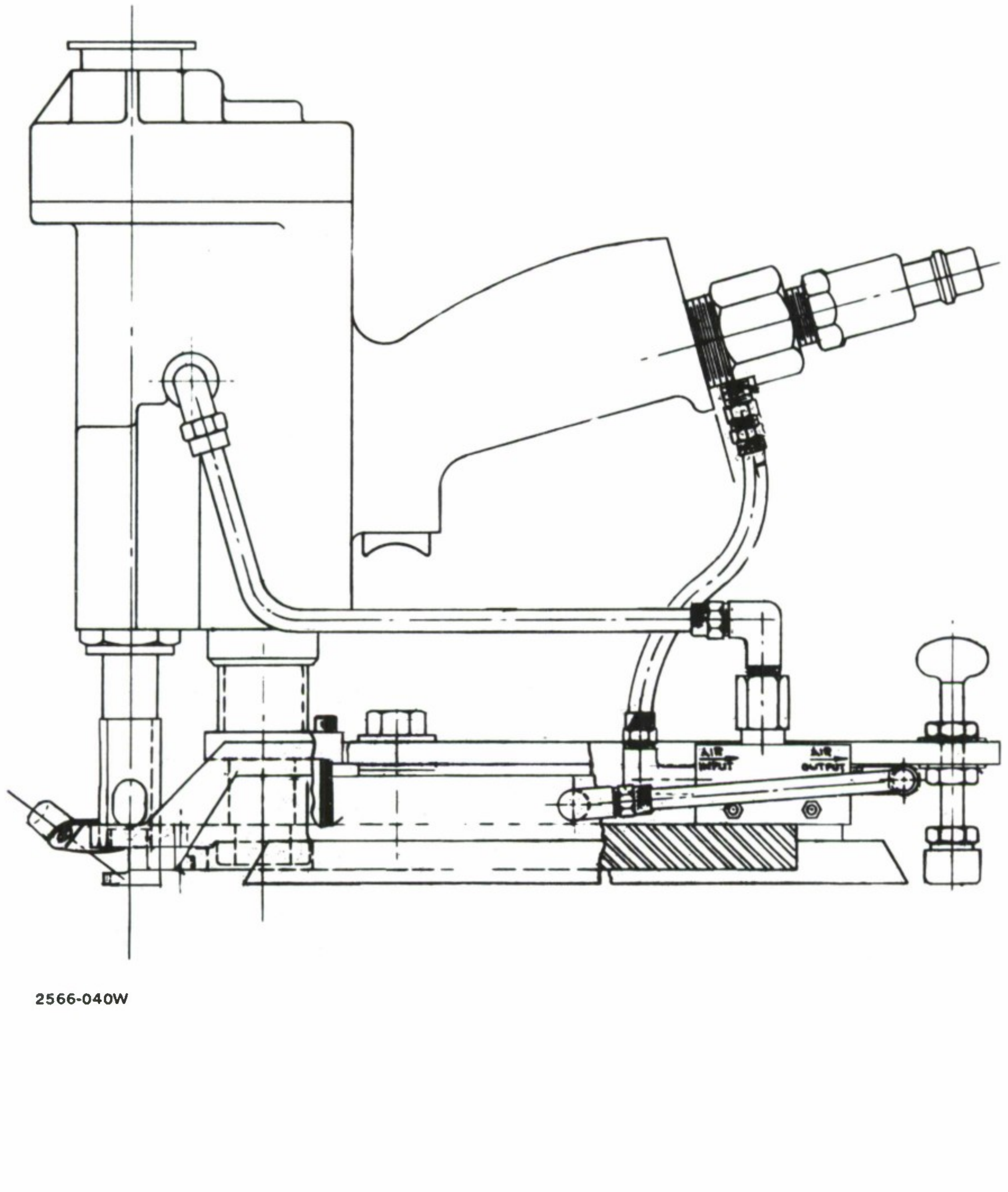

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Figure 5-22 Winslow Spacematic Drill Modified with Vacuum Pads

When compared to offhand drilling, high-speed, low-feed, no-dwell, in-out drilling conditions increased tool life 5 to 10 times over that for offhand techniques. For example, the M-62 Spacematic test at 6000 rpm and 0.001 ipr provided 107 holes for 0.006-inch drill wear land development. Comparable results were obtained with the same equipment on the B-1 program where an average of 75 holes were obtained when drilling at 6000 rpm and 0.001 ipr through a 0.47-inch-thick average graphite/epoxy stackup.

B-1 production life for carbide drills used in the offhand mode, however, was generally limited to a minimum of 10 holes. It should be noted that part of this requirement was to conserve the drill for resharpening. However, it can readily be observed that a considerable increase in life is obtained when drilling in the portable mode as compared to the offhand mode.

Offhand drilling is usually limited to a speed of 1100 rpm. Beyond that, there is a tendency for operators to throttle the motor down to a lower, more controllable speed, or to jog through the hole. Both conditions reduce tool life and produce poor surface finish. The advantage of offhand drilling is that it is a cost-effective method, readily available to the airframe industry for drilling holes in confined quarters or in structures requiring many small-diameter fasteners.

When aluminum backup washers were used in the B-1 horizontal stabilizer, tool life decreased to an average of 40 holes (47 percent) per drill with the M-62 Spacematic unit. To assure that no delamination would occur between aluminum and graphite, sharp drill points were maintained.

5.3.3 Graphite-Boron/Epoxy Hybrid Drilling

Hybrid drilling can be accomplished by either stationary or portable ultrasonic equipment. Stationary drilling of the B-1 horizontal stabilizer, which is backed up by a titanium structure, is discussed below. Holes were generated in two basic steps: (1) ultrasonic drilling/countersinking, and (2) transfer drilling. Also discussed is a portable ultrasonic drill which was developed during the course of the program.

5.3.3.1 Hybrid Drilling - A special ultrasonic drilling fixture was used for drilling and countersinking graphite/epoxy and boron-graphite/epoxy hybrid areas of the B-1 horizontal stabilizer (Figures 5-23 and 5-24). The power supply provides 600 watts to the drill spindle resonator at a frequency of 20 kHz. This provides 0.0007 to 0.001 in. peak amplitude at the spindle end. The drill machine has an infinite feed range with speeds to 10,000 rpm. This unit can be stationary or on a gantry for drilling the hybrid areas of the B-1 horizontal stabilizer. The stabilizer cover is supported horizontally in a specially designed fixture. The UMT-5 rotary ultrasonic machine head rolls on the contoured rails in such a manner that the spindle is automatically positioned perpendicular to the air-passage surface when the spindle template boss is located in the template. The spindle is fitted with a specially designed micrometer-adjustable countersink depth control. The drill machine tools are water-cooled. Tools used are all-diamond types - either sintered or coated. The machine is versatile in that it can drill, countersink, ream, and counterbore. For the B-1 program, the cutting tools were of an improved design to maintain dimensional accuracy and lower costs. The ultrasonic drill-countersink is fitted with a sintered diamond core drill plus an electroplated nickel/diamond sizing band behind the tip to maintain size and concentricity. The countersink surface is also plated because it can be stripped chemically and replated at low cost to extend tool life.

This application utilized specially designed, diamond, core-drill/countersink combination tools ranging from 0.190-inch to 0.500-inch diameter (Figure 5-25). The core drill portion of the drill is a sintered metal matrix, slotted at the drill end. Core drill ID is 0.010-inch eccentric to the OD for slug removal. Above the 0.25-inch-wide sintered portion of the core drill is a plated sleeve section which performs the sizing operation. This plated sleeve is 0.25 inch wide and 0.005 inch larger in diameter than the sintered portion. The countersink surface is also plated and contains three unplated relief areas, 120° apart.

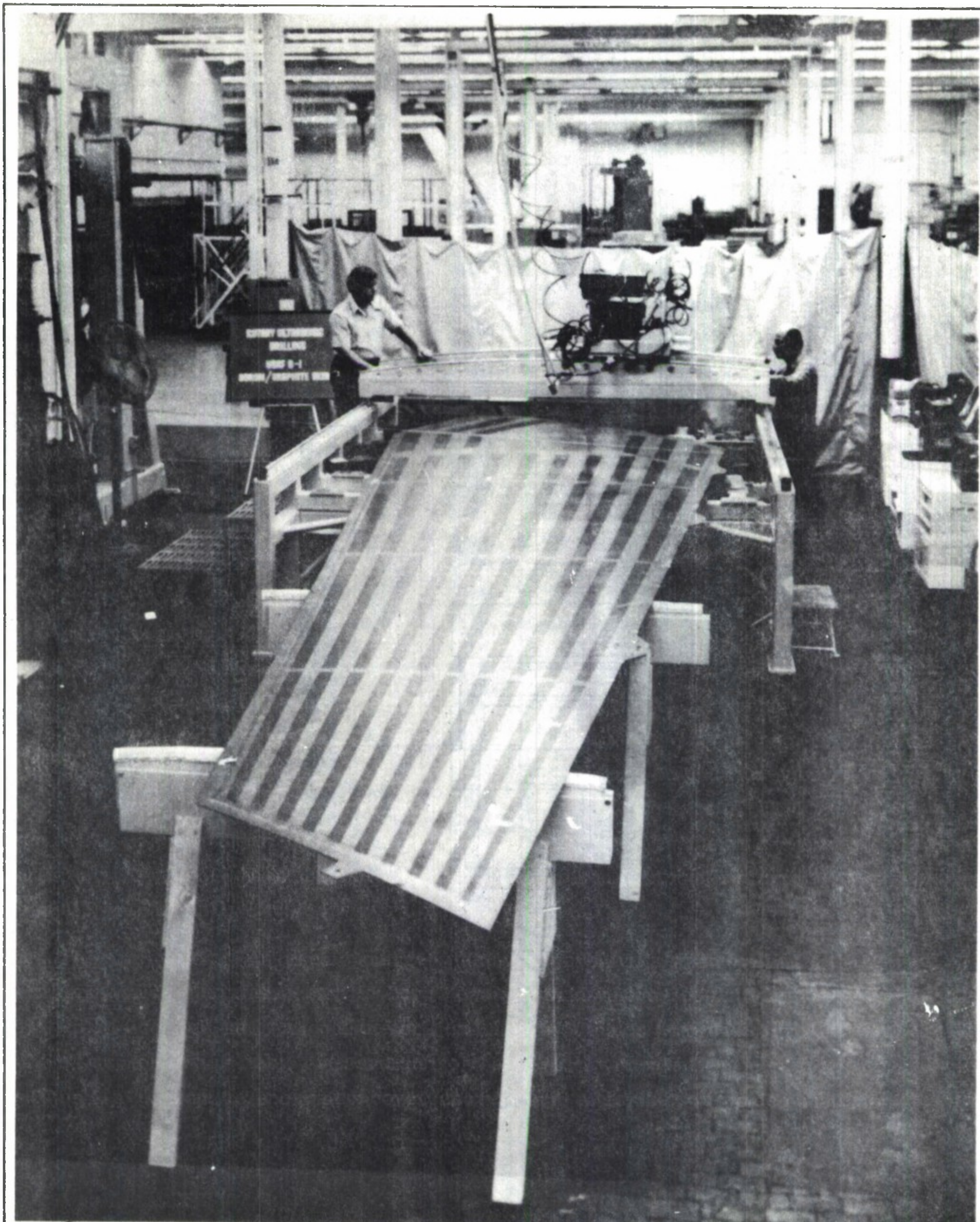

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Figure 5-23 Ultrasonic Drilling Fixture for Hybrid Cover of B-1 Horizontal Stabilizer

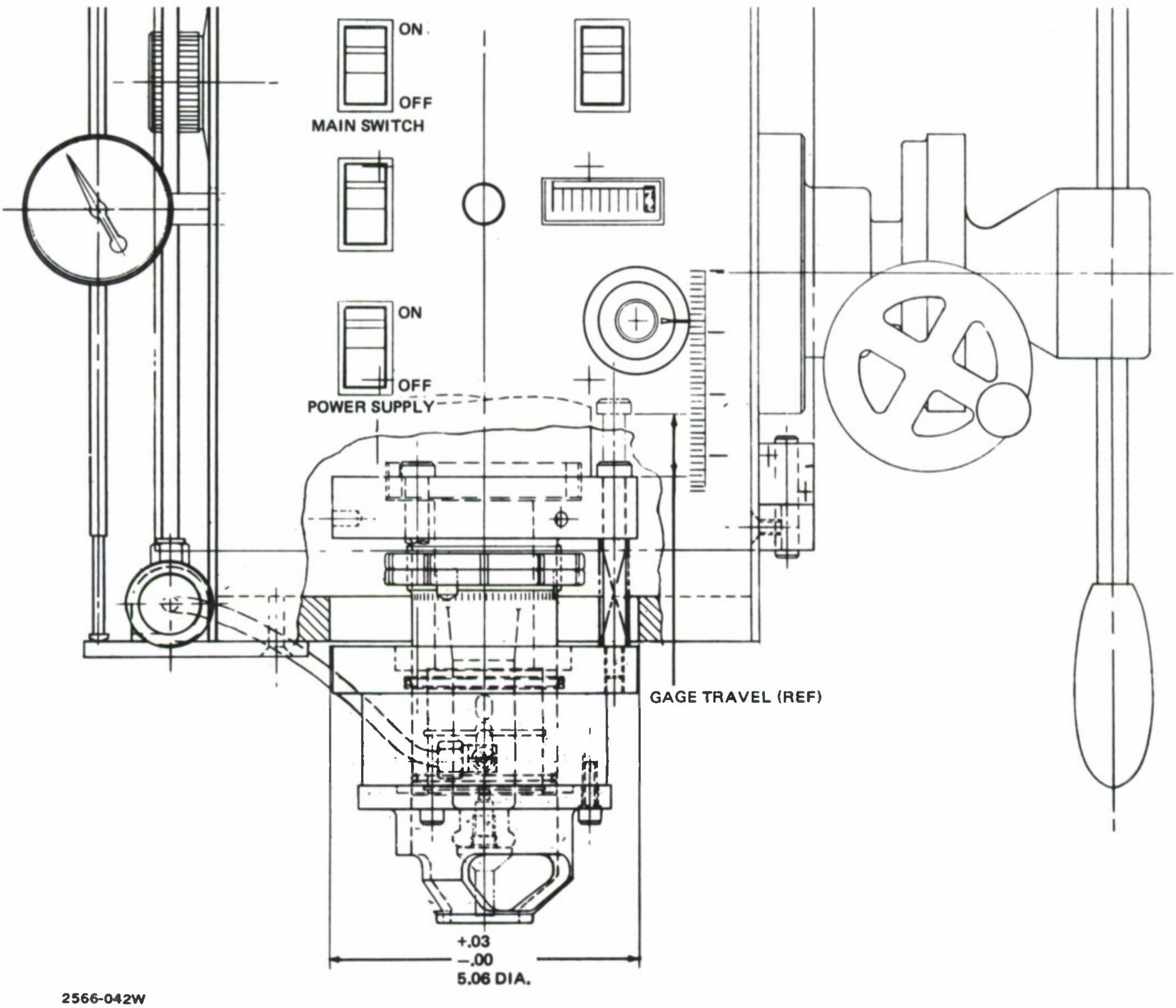

Figure 5-24 UMT-5 Ultrasonic Drilling Unit

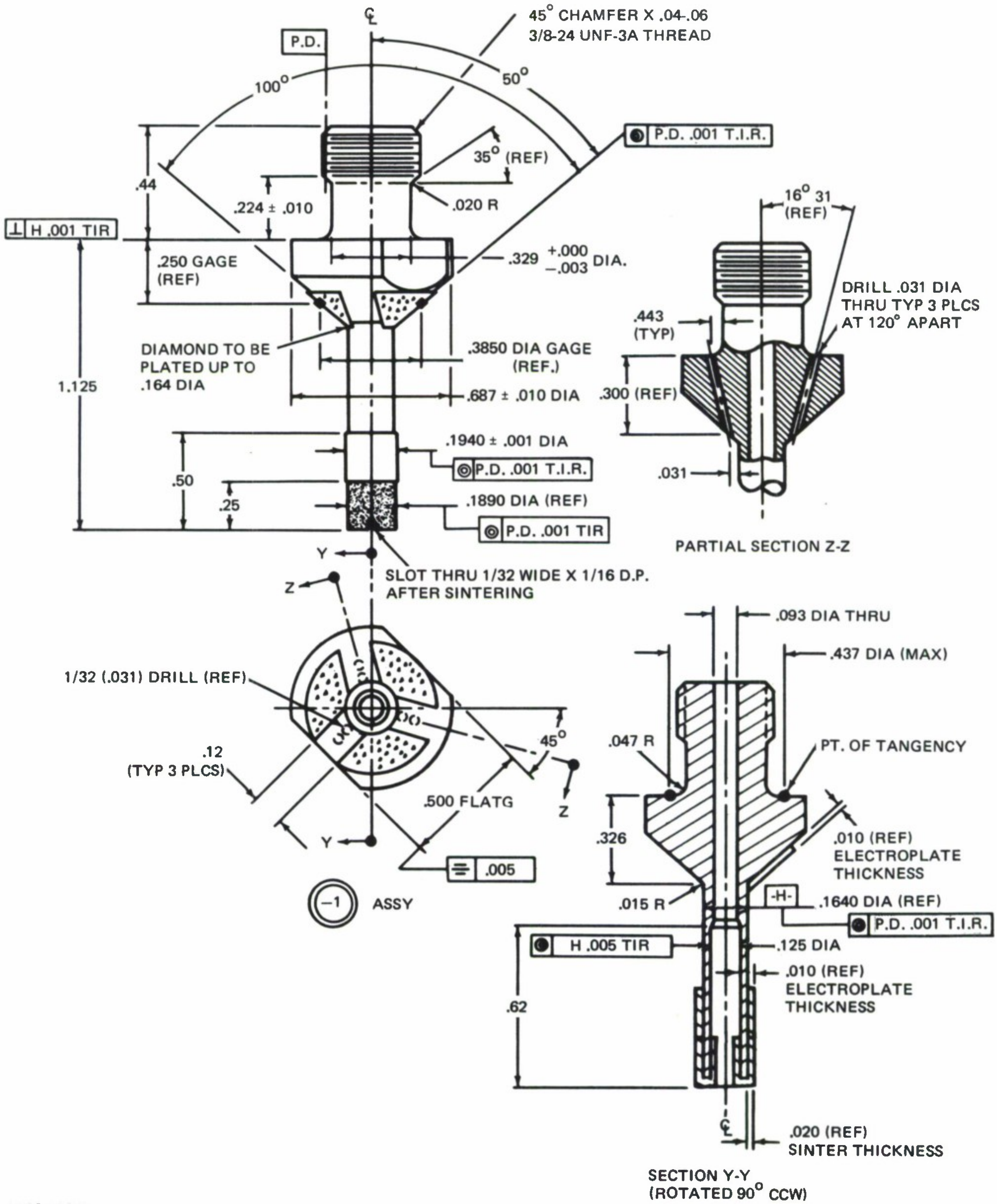

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Figure 5-25 Diamond Drill/Countersink Combination Tool (0.199D)

During the drilling operation coolant is passed down the core drill. On breakout, a spindle valve is activated in the unit, shutting off core drill flow and directing it into the countersink at the unplated surface. Production life was 150 holes for smaller tools to 75 holes for the 0.050-inch tool. Highest wear was experienced on the countersink portion of the tool. The drill tip could be dressed for continued usage; however, countersink wear required tool removal from service. Drill-tip life was approximately three times that of the countersink life. Although more wear could be tolerated on the drill, a minimum diameter was still maintained in order to accept the hone used on the next operation. It should be noted that the greater wear was anticipated in the larger diameter tools, since greater concentration of boron exists in the larger diameter fastener area. The further outboard, the greater the number of small fasteners and the less boron used. When worn, these tools were refurbished by chemical stripping of the worn plating and replating with diamonds in solution. An electroless-nickel bond is common. Replating costs approximately one-third that of the original tool. The above tools were run at the resonant frequency. Tool weight ranged from 35 to 60 grams, with the heavier tools operating in the lower frequency range. Frequencies used were 19300 to 20100 Hz.

5.3.3.2 Portable Hybrid Drilling - Drilling tests were conducted using a Quackenbush 158 QC DABV portable drilling machine with an ultrasonic adaptor (see Figure 5-26) and powered by a Branson Model UD-12 (150 watt) power supply (Figure 5-26). Tests were conducted at 3,000 rpm with 0.0005 ipr feed, using a water coolant and a 3/16-inch-diameter diamond-sintered core drill. Two-hundred holes were drilled in graphite/epoxy plus boron/epoxy (40%/60%) hybrid. The diametrical wear for the drill was only 0.0009 inch and the hole diameter decreased 0.0017 inch for the 200 holes. No problem was encountered with material core ejection from the drill.

The application of ultrasonic energy to diamond core drills when drilling either boron/epoxy plus fiberglass/epoxy or boron/epoxy hybrids increased drill life. As reported by Rockwell International (Reference 9), only 50 holes (average) were obtained using a Quackenbush portable drill and diamond core drill without ultrasonics for 0.40-inch-thick graphite/epoxy plus boron/epoxy hybrid materials. This demonstrated

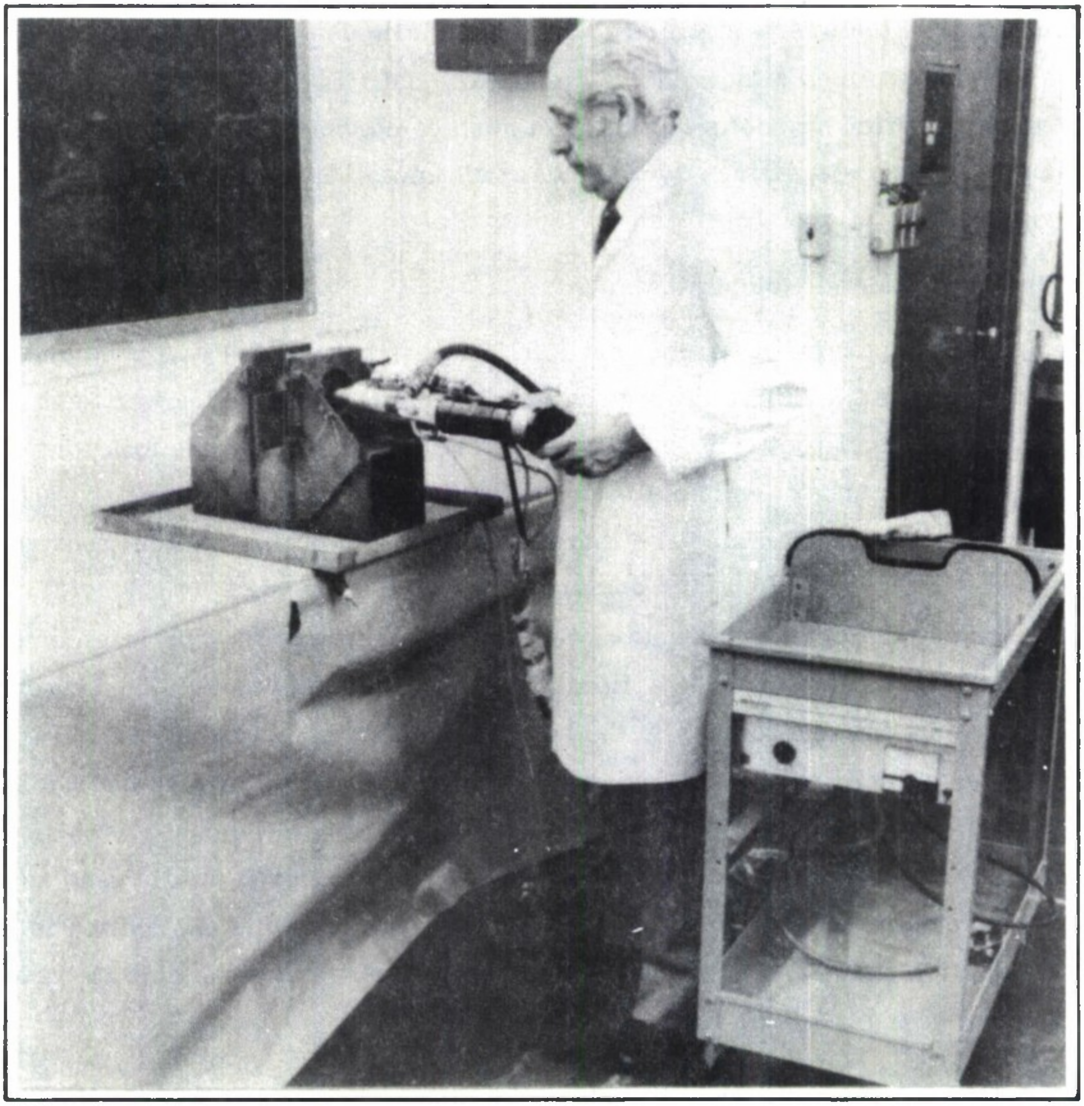

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Figure 5-26 Drilling of Graphite/Epoxy Plus Boron/Epoxy Hybrid with Ultrasonically Adapted Quackenbush Model 158 QC DABV Poratble Machine that application of ultrasonic energy resulted in an equivalent increase of 100 percent (200 holes in 0.220-inch-thick hybrid)

5.3.4 Honing

The B-1 hybrid fastener holes discussed in the preceding stationary ultrasonic drilling section required a precision tolerance of ±0.0005 inch and, therefore, were drilled undersize to the low side of the tolerance followed by honing to the final size. The honing operation was performed with the specially designed tool shown in Figure 5-27. This tool utilizes a tapered nose piece to locate itself with respect to the 100° countersink and three standoffs to establish surface normality. The hone is a 220-grit diamond Flex-o-lap driven by a standard air motor at 450 rpm using Freon TB-1 coolant.

5.3.5 Hybrid-to-Metal Hole Transfer

A Winslow Spacematic air-powered drill unit (Figure 5-21) was used on theB-1 horizontal stabilizer. This tool provides good clamping force and power feed for drilling in the critical root connection holes. The unit is used in the following manner: First, an undersized hole is drilled adjacent to hole to be drilled. The mandrel and collet are then inserted into the hole drilled in the titanium root area to allow the collet to pull up on the mandrel which grips the edges of the hole, thereby securing the drill and counteracting the drilling thrust. This is repeated for each hole. An undersized hole is drilled through the titanium using a bushing nose-piece on the drill gun that locates in the holes drilled in the hybrid cover. The subsequent cover drilling and recurring operations are located by a countersink-shaped nosepiece on the drill gun which is positioned on the previously ultrasonically countersunk holes in the hybrid cover. In this way, the cover is really used as a drill plate to ensure alignment of the holes. Noteworthy for this application is the reamer selection (left-hand helix, right-hand cut) which causes the chip to travel in a direction away from the final sized composite holes.

5.3.6 Wet Versus Dry Drilling

Several tests were conducted on a Dumore drilling machine at a speed of 6,000 rpm and a feed of 0.001 ipr. Test No. 40 was conducted with a carbide-tipped, 1/4-inch-diameter drill on graphite/epoxy workpiece material. This test was conduc-

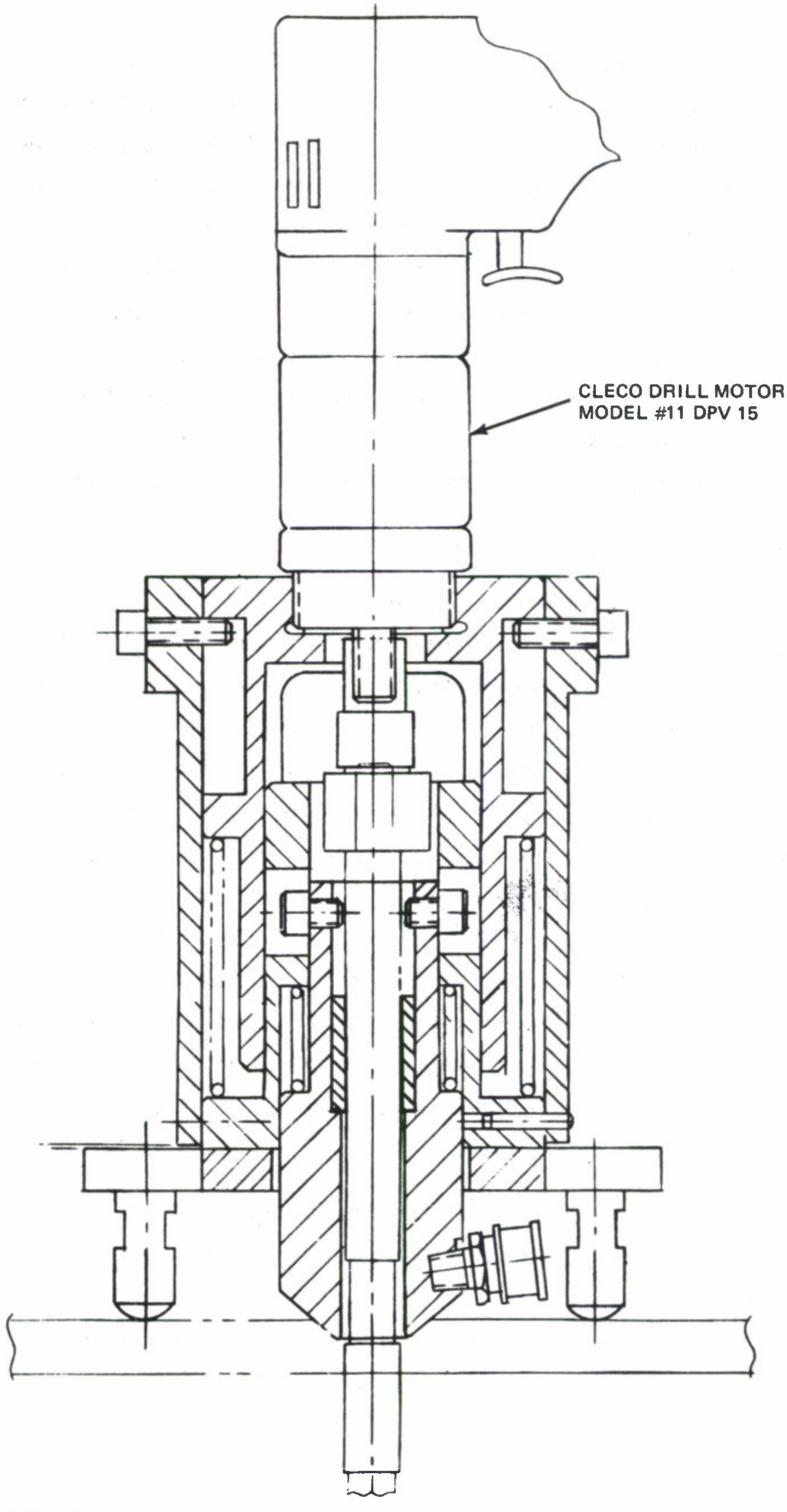


Figure 5-27 Manual Honing Tool

ted to obtain dry/wet comparisons and tool-life projections at various speeds for the same feed. Analysis of the test results indicates that greater tool life is achieved at 6,000 rpm when drilling dry. Figure 5-28 shows that tool life improves with increasing speed. Test No. 41 was conducted with a solid carbide, 3/16-inch-diameter drill. This test was also conducted to obtain dry/wet comparisons and tool-life projections at various speeds for the same feed. Test results were similar to those obtained in Test No. 40. Although it would be expected that use of a coolant would extend drill life because drill temperature is kept down, conclusive data to this effect cannot be established. On the contrary, Tests 40 and 41 showed that tool life was extended by drilling dry. A good vacuum system is required for dry drilling, because it effectively removes chips and reduces temperature by eliminating chip congestion.

5.3.7 Controlling Exit Delamination

A major concern when drilling laminates of graphite/epoxy without a backing material is exit delamination. Controlled tests indicate that the factor contributing most to delamination control was maintaining a constant feed rate. Lower feed rates per revolution created the least amount of axial thrust, thereby causing less exit breakout; however, feed rates less than 0.001 ipr cause breakout to occur. Results obtained during high-speed drilling tests at 21,000 rpm and 0.001 ipr showed acceptable holes and minimal breakout without any back-up material. Drilling tests conducted at 21,000 and 6,000 rpm at a feed rate of 0.001 ipr using fiberglass/epoxy laminate backups gave excellent holes with no breakout on the back side. Spot-checking of several of the other drilling tests in which fiberglass/epoxy laminates were also used to backup the workpieces showed that use of the backup material effectively eliminated hole breakout. Another effective approach to delamination control involves use of a peel ply and the addition of a primary bonded fiberglass furring strip on the exit side.

A breakout evaluation test was conducted to determine the effect of bonding two plies of fiberglass/epoxy to graphite/epoxy on the drill exit side. A 0.250-inch-diameter carbide-tipped drill mounted in a Dumore drill machine was run at 6000 rpm and 0.001 ipr feed (Test No. 43). Results showed that starring of the bonded fiberglass/epoxy plies occurred after only a few holes had been drilled. When the bonded fiberglass/epoxy plies were removed from the last two drilled holes, however, the graphite/epoxy substrate had not delaminated on the exit side. Compared to Test No. 40, in which no backup was used for drilling graphite/epoxy at identical parameters, all holes were delaminated on the exit side. Based on wear-land development (0.006 inch limit) and equivalent thicknesses, 15 percent or 10 fewer holes were drilled in this material than were drilled in the graphite/epoxy without the two bonded plies of fiberglass/epoxy. There is also, obviously, a weight penalty to consider with this approach.

TEST NO.	TYPE OF DRILL	DRILL DIA., IN.	FEED, IPR	TOOL LIFE, IN.	MATERIAL THICKNESS, IN.	NUMBER OF HOLES DRILLED	SPEED, SFM	DRILL SPEED, RPM	MATERIAL CUT, LINEAR FEET
32	CARBIDE-TIPPEO	0.250	0.001	0.006	0.275	40	687	10500	720
						80	1375	21000	1440
30	SOLIO CARBIDE	0.190	0.001	0.006	0.275	290	1045	21000	3967
90*	CARBIDE-TIPPED	0.250	0.001	0.006	0.275	50	393	6000	900
28*	SOLIO CARBIOE	0.190	0.001	0.006	0.275	140	298	6000	1915
40	CARBIOE-TIPPED	0.250	0.001	0.006	0.270	70	393	6000	1237
41	SOLID CARBIDE	0.188	0.001	0.006	0.270	150	295	6000	2000

NOTES:

TOOL-LIFE END-POINT EXPRESSEO IN TERMS OF WEAR LAND DEVELOPMENT
*COOLANT USED – HANGSTERFER'S HE2 20:1 MIX

2566-046W

Figure 5-28 Summary of Graphite/Epoxy Drilling Tests with Carbide Tools

Section 6

PHASE III - MACHINING CURED LAMINATES

The latest manufacturing techniques were assessed to establish low-cost methods of material removal for cured composites. Controlled machining tests were performed for routing, trimming, beveling, countersinking, and counterboring. Equipment reliability, detrimental effects, edge quality, ease of operation, and operating costs were also established.

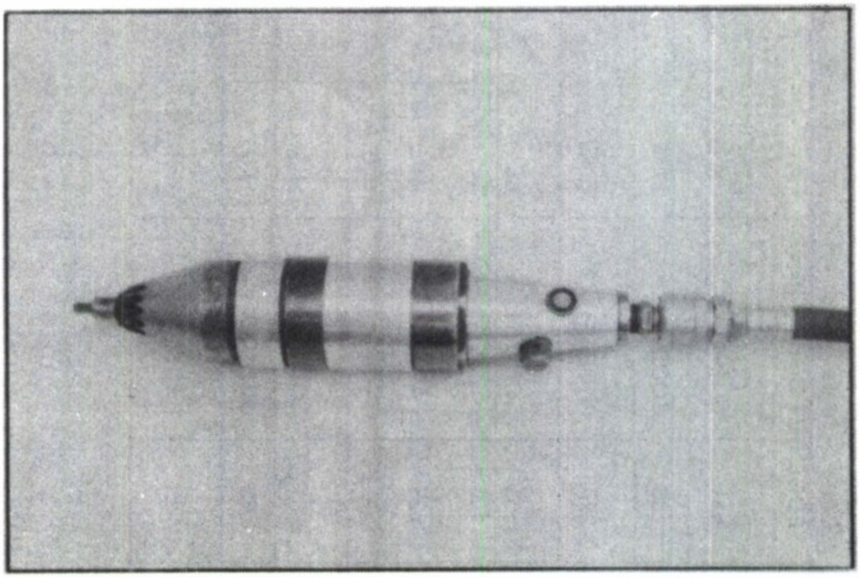
6.1 ROUTING, TRIMMING AND BEVELING

Routing, trimming, and beveling operations are essentially equivalent, involving use of similar types of equipment such as hand routers and mechanical Marwin machine routers and Roto-Recipro machines. Diamond-cut carbide and four-fluted milling cutters were used to machine graphite/epoxy and fiberglass/epoxy laminates. Carbide, opposed-helical router bits were used to machine Kevlar/epoxy and Kevlar-graphite/epoxy hybrids. Diamond-coated router bits were used with the Roto-Recipro machine to rout and trim boron/epoxy and boron-graphite/epoxy hybrids. Speeds for these operations ranged from 3,600 to 45,000 rpm.

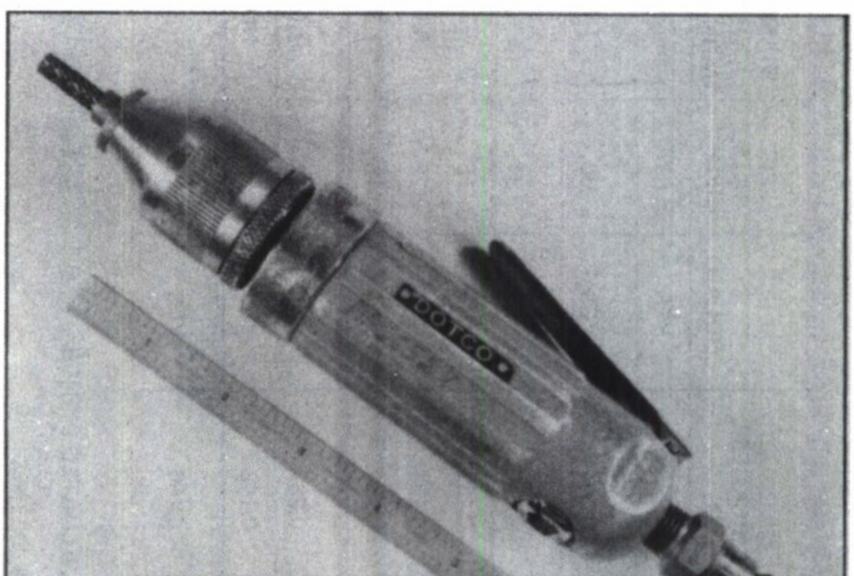
6.1.1 Portable Routing and Trimming

Manual routing tests were performed with a 13,000-rpm Buckeye router and a 22,000 Dotco router (Figure 6-1). The Buckeye router operates at lower speeds than the Dotco router, but generates more torque. Cutting tools used in these routing tests were either diamond-cut carbides or 6-flute carbide routers, all 0.25-inch in diameter. When used, the coolant was a water solution of Hangsterfers HE-2 fluid. Full-depth plunge cuts were made in all cases. Results of the manual routing tests on cured composites are summarized in Figures 6-2 and 6-3.

In general, these preliminary tests showed that the higher torque, Buckeye router gave the best cutting capability. The diamond-cut carbide router bits attained higher feedrates at less operator effort than did the 6-flute configuration. Use of the coolant tended to extend tool life and increase the cutting force (probably due to sludge formation) with no effect on cut-edge quality. Based on operator effort, maximum diametral tool wear would be about 0.0015 inch before tool change would be required. Typical edge quality of manually routed, 0.129-inch-thick graphite/epoxy panels is shown in Figure 6-4.



a. Buckeye Router



b. Dotco Router

2566-047W

Figure 6-1 Portable Manual Routers

MATERIAL	THICKNESS, IN.	COOLANT	FEED RATE, IPM	DIAMETRAL WEAR, IN./IN.^{3} x 10^{-4}	EDGE CUT CONDITION		THRUST EFFORT REQ'D TO MAKE CUTS
					RMS	CUT QUALITY	
GRAPHITE/EPOXY	0.066	YES	83	7.7	63	GOOD	LOW
GRAPHITE/EPOXY + KEVLAR/EPOXY	0.064	YES	60		>250	POOR (FUZZY)	LOW
GRAPHITE/EPOXY + FIBERGLASS/EPOXY	0.064	YES	84		63	GOOD	LOW
GRAPHITE/EPOXY	0.132	YES	15	4.2	63	GOOD	AVERAGE
	0.132	NO	22	5.1	125	FAIR	AVERAGE
	0.272	YES	10	1.5	1	------	HIGH
GRAPHITE/EPOXY + KEVLAR/EPOXY	0.287	YES	14	1.0	1	------	HIGH
FIBERGLASS/EPOXY	0.148	YES	27	NONE	63	GOOD	LOW
GRAPHITE/EPOXY + FIBERGLASS/EPOXY	0.266	YES	16	6.3	125	FAIR	VERY HIGH

NOTE:
1 SAMPLES EVALUATED BY NDE

CONDITIONS:
SPEED – 13,000 RPM
– 851 SFM
CARBIDE CUTTER TYPE – DIAMOND CUT

TYPE OF ROUTING – PLUNGE CUT
COOLANT – HANGSTERFERS – HE-2 WATER SOLUTION

Figure 6-2 Summary of Manual Routing (Buckeye Router) of Cured Composites

2566-048W

MATERIAL	THICKNESS, IN.	CARBIDE CUTTER TYPE	COOLANT	FEED RATE, IPM	DIAMETRAL WEAR, IN./IN.^{3} x 10^{-4}	EDGE CUT CONDITION		THRUST EFFORT REQD TO MAKE CUTS
						RMS	CUT QUALITY	
GRAPHITE/ EPOXY	0.066	DIAMOND CUT	YES	28	1.8	60	GOOD	LOW
GRAPHITE/ EPOXY	0.132	DIAMOND CUT RESHARP CUTTER	YES	11	5.2	60	GOOD	AVERAGE
GRAPHITE/ EPOXY	0.132	6 FLUTES	YES	6.7	7.6	60	GOOD	HIGH
GRAPHITE/ EPOXY	0.272	DIAMOND CUT	YES	5	4.3	(1)		HIGH
GRAPHITE/ EPOXY + KEVLAR/ EPOXY	0.066	DIAMOND CUT	YES	23.4	NONE	>250	POOR (FUZZY)	LOW
GRAPHITE/ EPOXY + KEVLAR/ EPOXY	0.270	DIAMOND CUT	YES	4.1	3.7	>250	POOR (FUZZY)	HIGH
FIBERGLASS/ EPOXY	0.148	DIAMOND CUT	YES	15	8.4	60	GOOD	LOW
GRAPHITE/ EPOXY + FIBERGLASS/ EPOXY	0.064	DIAMOND CUT	YES	30	1.7	60	GOOD	LOW
GRAPHITE/ EPOXY + FIBERGLASS/ EPOXY	0.266	DIAMOND CUT	YES	—	—	—	—	NOT PRACTICAL TO CUT

NOTE:
(1) SAMPLES EVALUATED BY NDE
CONDITIONS:
SPEED – 22,000 RPM
– 1435 SFM
COOLANT – HANGSTERFERS HE-2, 20-1 WATER SOLUTION
TYPE OF ROUTING – PLUNGE CUT

2566-049W

Figure 6-3 Summary of Manual Routing (Dotco Router) of Cured Composites

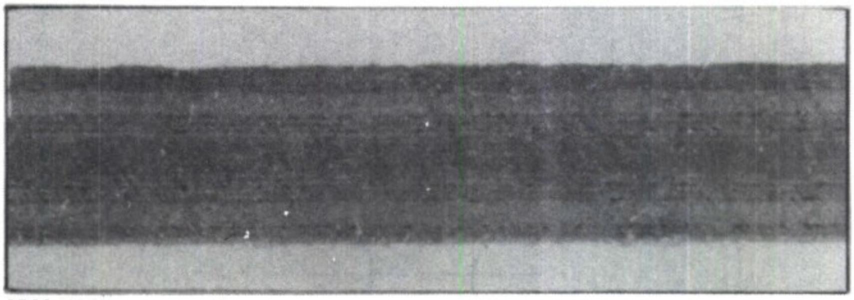
Manual trimming and beveling tests were performed with the same 13,000-rpm Buckeye router against a guide. The materials used in these tests were graphite/epoxy, fiberglass/epoxy, Kevlar/epoxy and graphite/epoxy plus fiberglass/epoxy hybrid. The router bits were 0.25-inch-diameter, diamond-cut carbide types. The coolant, when used, was a water solution of Hangsterfers HE-2 fluid. Full-thickness cuts were made in all cases. The depths of the cuts were either 0.06 or 0.13 inch and 45° x 1/8 or 1/4-inch. Results of these manual trimming and beveling tests on cured composites are summarized in Figure 6-5. In general, good cuts were made on thicknesses up to 0.272 inch. The quality of the trimmed edges could be improved by subjecting the workpieces to a second trimming operation. Kevlar/epoxy trimmed edges were of fair quality and could be improved by sanding with 100 to 180-grit abrasive paper.

6.1.2 Stationary Routing of Kevlar/Epoxy

An opposed-helix, carbide cutter (Figure 6-6) was developed by Pen Associates, Inc., Wilmington, Delaware, for routing cured Kevlar/epoxy laminates. It was recommended that this cutter be run at high speeds in a rigid spindle and that it enter the workpiece at the juncture of the opposing helix. As a result, routing tests were conducted on an Onsrud router (Figure 6-7a) where these conditions could be met. Data obtained are presented in Figure 6-8. The opposed-helix, carbide cutter performed better than diamond-cut carbide cutters in a portable mode with Kevlar/epoxy and graphite/epoxy plus Kevlar/epoxy laminates. Although cut quality was about equivalent for both types of cutters, only the opposed-helix, carbide cutter could trim 1/4-inch-thick material. In general, cut quality was fair. It should be noted that the quality of cut was substantially better on the climb-mill side than on the conventional mill side for the opposed-helix cutter.

6.1.3 Marwin Machine Routing

The principal limitations of manual routing and trimming are that high cutting forces are required and productivity is highly dependent on operator skill. Use of the Marwin profiler in composite machining operations will negate these limitations because feeds can be controlled while maintaining constant speed. Although the Marwin machine used in these tests (Figure 6-7b) did not have automatic feed, it was mechanically operated with positive feed. Test results are presented in Figure 6-9. The slower feed rates tended to give better cut quality. Tool wear, feed rates and



2566-050W

Figure 6-4 Typical Edge-Quality of 0.129-Inch Thick, Graphite/Epoxy Panel Manually Routed with Buckeye Router at 13,000 RPM (7x Mag)

MATERIAL	THICKNESS, INCH	FEED RATE, IPM	DEPTH OF CUT, INCH	DIAMETRAL WEAR, IN./IN.^{3} x 10^{-4}	EDGE CUT CONDITION		THRUST EFFORT REQD TO MAKE CUTS
					RMS	CUT QUALITY	
TRIMMING:							
GRAPHITE/EPOXY	0.091	87	0.06	6.5	32	GOOD	AVERAGE
GRAPHITE/EPOXY	0.091	53	0.13	4.0	32	GOOD	AVERAGE
GRAPHITE/EPOXY	0.272	23	0.06	1.0	125	FAIR	HIGH
GRAPHITE/EPOXY	0.272	15.3	0.13	0.9	250	POOR	HIGH
GRAPHITE/EPOXY PLUS FIBERGLASS/EPOXY	0.062	160	0.06	N/A	32	GOOD	LOW
GRAPHITE/EPOXY PLUS FIBERGLASS/EPOXY	0.245	68.4	0.06	1.1	32	GOOD	HIGH
FIBERGLASS/EPOXY	0.148	58.5	0.06	0.6	32	GOOD	AVERAGE
FIBERGLASS/EPOXY	0.148	53	0.13	0.9	32	GOOD	AVERAGE
KEVLAR/EPOXY	0.123	46.2	0.06	1.3	125	FAIR (FUZZY OUTER FIBERS)	HIGH
BEVELING:							
GRAPHITE/EPOXY	.272	47	45° x .200	0.34	32	GOOD	AVERAGE
GRAPHITE/EPOXY PLUS FIBERGLASS/EPOXY	.245	58	45° x .200	0.25	32	GOOD	AVERAGE
FIBERGLASS/EPOXY	.148	57	45° x .13	0.5	32	GOOD	AVERAGE

CONDITIONS:
- CUTS – ALL FULL THICKNESS EXCEPT FOR BEVELING
- ROUTER – BUCKEYE
- SPEED (RPM) – 13000
- (SFM) – 851
- CARBIDE CUTTER TYPE – DIAMOND CUT (THESE WERE RESHARPENED FOR TRIMMING AND NEW FOR BEVELING)
- COOLANT: HANGSTERFERS – HE 2 (20:1 MIX) WATER SOLUTION USED FOR ALL CUTS.

2566-051W

Figure 6-5 Summary of Manual Trimming and Beveling of Cured Composites

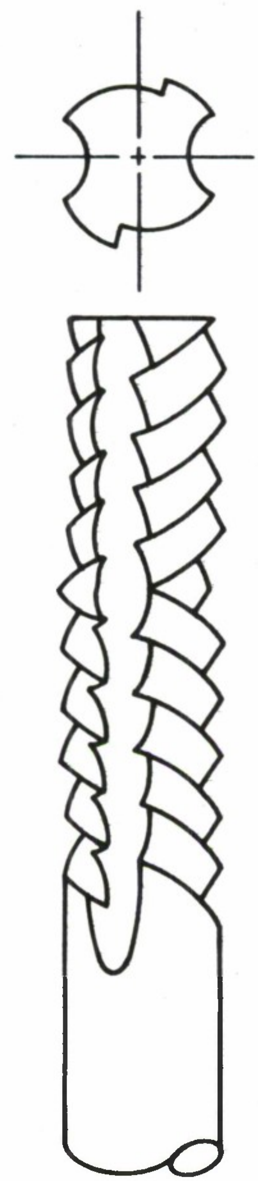
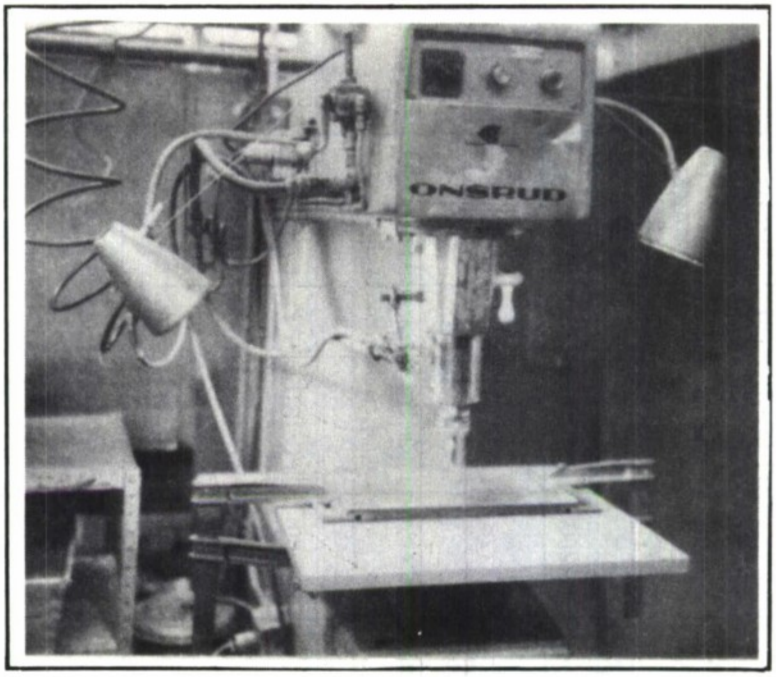
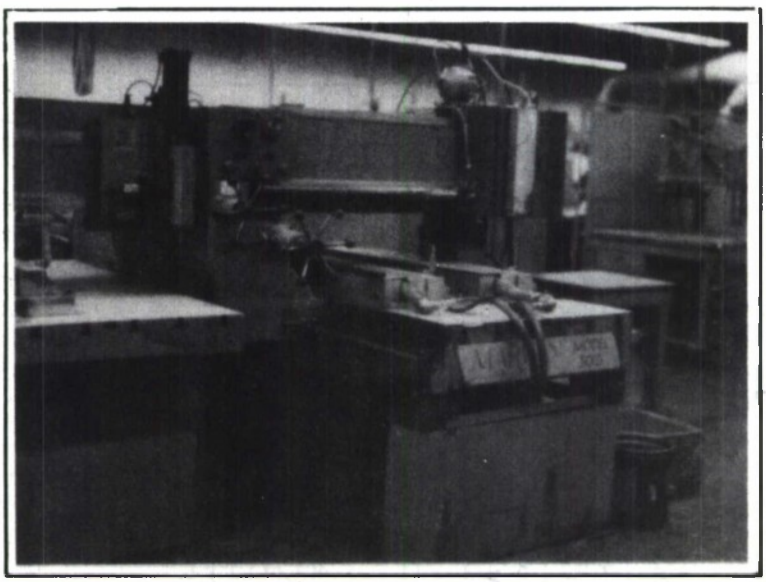


Figure 6-6 Opposed Helical Router Bit for Trimming Kevlar/Epoxy

2199-164B



a. Onsrud



b. Marwin

2566-052W

Figure 6-7 Stationary Routers

OPERATION	MATERIAL	THICKNESS, IN.	FEED RATE, IPM	DEPTH OF CUT, IN.	DIAMETRAL WEAR, IN./IN.^{3} x 10^{-4}	EDGE CUT CONDITION		THRUST EFFORT REQ'D. TO MAKE CUTS
						FINISH, RMS	CUT QUALITY	
ROUTING	GRAPHITE/EPOXY +KEVLAR/EPOXY	0.064	44	FULL	1.7	>250	POOR(FUZZY)	LOW
	GRAPHITE/EPOXY +KEVLAR/EPOXY	0.263	8	FULL	1.9	125	FAIR(FUZZY)	HIGH
	KEVLAR/EPOXY	0.102	59	FULL	N/A	>250	CONV CUT POOR (CLIMB CUT GOOD)	LOW
TRIMMING	GRAPHITE/EPOXY +KEVLAR/EPOXY	0.064	76	0.13	14.7	>250	POOR(FUZZY)	LOW
	KEVLAR/EPOXY	0.102	64	0.13		125	FAIR(FUZZY)	AVERAGE
	GRAPHITE/EPOXY +KEVLAR/EPOXY	0.263	35	0.13	1.3	125	FAIR(FUZZY)	AVERAGE

CONDITIONS: ROUTER-ONSRUD MACHINE
SPEED-20,000 RPM
CARBIDE CUTTER TYPE-OPPOSED HELIX (PEN ASSOCIATES, INC.)
COOLANT-NONE

2566-053W

Figure 6-8 Summary of Stationary Routing and Trimming of Cured Composites

MATERIAL	THICKNESS, IN.	FEED RATE, IPM	DIAMETRAL WEAR, IN./IN.^{3} x 10^{-4}	EDGE CUT CONDITION	
				RMS	CUT QUALITY
GRAPHITE/EPOXY	.086	29	2.4	63-125	FAIR
	.086	96		63-125	FAIR
GRAPHITE/EPOXY PLUS FIBERGLASS/ EPOXY	.062	24		125	FAIR
	.062	98		250	POOR, FUZZY
GRAPHITE/EPOXY	.287	12	2.5	125	FAIR
GRAPHITE/EPOXY PLUS FIBERGLASS/ EPOXY	.263	12	4.2	125	FAIR
FIBERGLASS/ EPOXY	.144	22	11.2	63	GOOD FUZZY ON EXIT EDGE
	.144	60		32-63	GOOD FUZZY ON EXIT EDGE

CONDITIONS:
ROUTER – MARWIN PROFILER
SPEED – 10,800 RPM
FEED – MECHANICAL/MANUAL
CARBIDE CUTTER TYPE – 3/8-INCH-DIAMETER; DIAMOND-CUT
COOLANT – HANGSTERFERS HE-2 (20-1) WATER SOLUTION
SPEED – 1,065 SFM
TYPE OF ROUTING – PLUNGE CUT

2566-054W

Figure 6-9 Summary of Machine (Marwin) Routing of Cured Composites

cut quality are equivalent to those obtained with the Buckeye router. A plot of tool wear for both portable and machine routing (shown in Figure 6-10) indicate little difference in tool wear between machine tools, but a large difference in wear when comparing new cutting tools to resharpened tools. The Buckeye router requires a great deal of effort when used to trim composite materials thicker than 1/8 inch. The Marwin router is limited to use with flat parts and simple formed parts.

6.1.4 Routing and Trimming of Boron/Epoxy

Routing and trimming tests of boron/epoxy and hybrid boron/epoxy plus graphite/epoxy laminates were conducted on a Roto-Recipro machine (Figure 6-11) using diamond-plated router bits. Analysis of the test results (Figure 6-12) show that when routing and trimming laminates less than 1/4-inch thick, good finishes were obtained at 60 and 200 reciprocating strokes per minute. Slight scalloping of the cut edges occurred on the thicker laminates at 60 strokes per minute; a little more scalloping occurred at 200 strokes per minute. The manual feed rates were held constant for each thickness at each reciprocating speed. As depicted in Figure 6-13, high wear rates are usually encountered when the router bit is first used due to wearing of the sharp diamond points. This was experienced previously when sawing boron/epoxy laminates and hybrid boron/epoxy laminates. The decrease in feed rate with increasing material thickness for Roto-Recipro routing, bevelling and trimming of boron/epoxy and trimming of boron/epoxy and boron/epoxy-graphite/ epoxy hybrids is shown in Figure 6-14.

6.2 COUNTERSINKING

Portable countersinking tests were performed on a Dumore drilling machine (simulates portable tool with air-over-oil feed system), a 21,000 rpm Gardner Denver drill, and in an off-hand (manual) mode. Materials evaluated were graphite/epoxy, fiberglass epoxy, Kevlar/ epoxy, graphite/epoxy plus fiberglass/ epoxy, and graphite/epoxy plus Kevlar/epoxy. The overall test matrix for countersinking and counterboring tests is shown in Figure 6-15. Although the objective of these tests was to establish effective tool materials, geometries and parameters, emphasis was placed on developing a countersinking capability in graphite/epoxy laminates that would be equivalent to the significant performance improvement achieved in high-speed drilling (280 holes at 21,000 rpm). In doing so, full cost advantage could be derived through a combination drill/ countersink tool. Results of these tests are summarized in Figure 6-16.

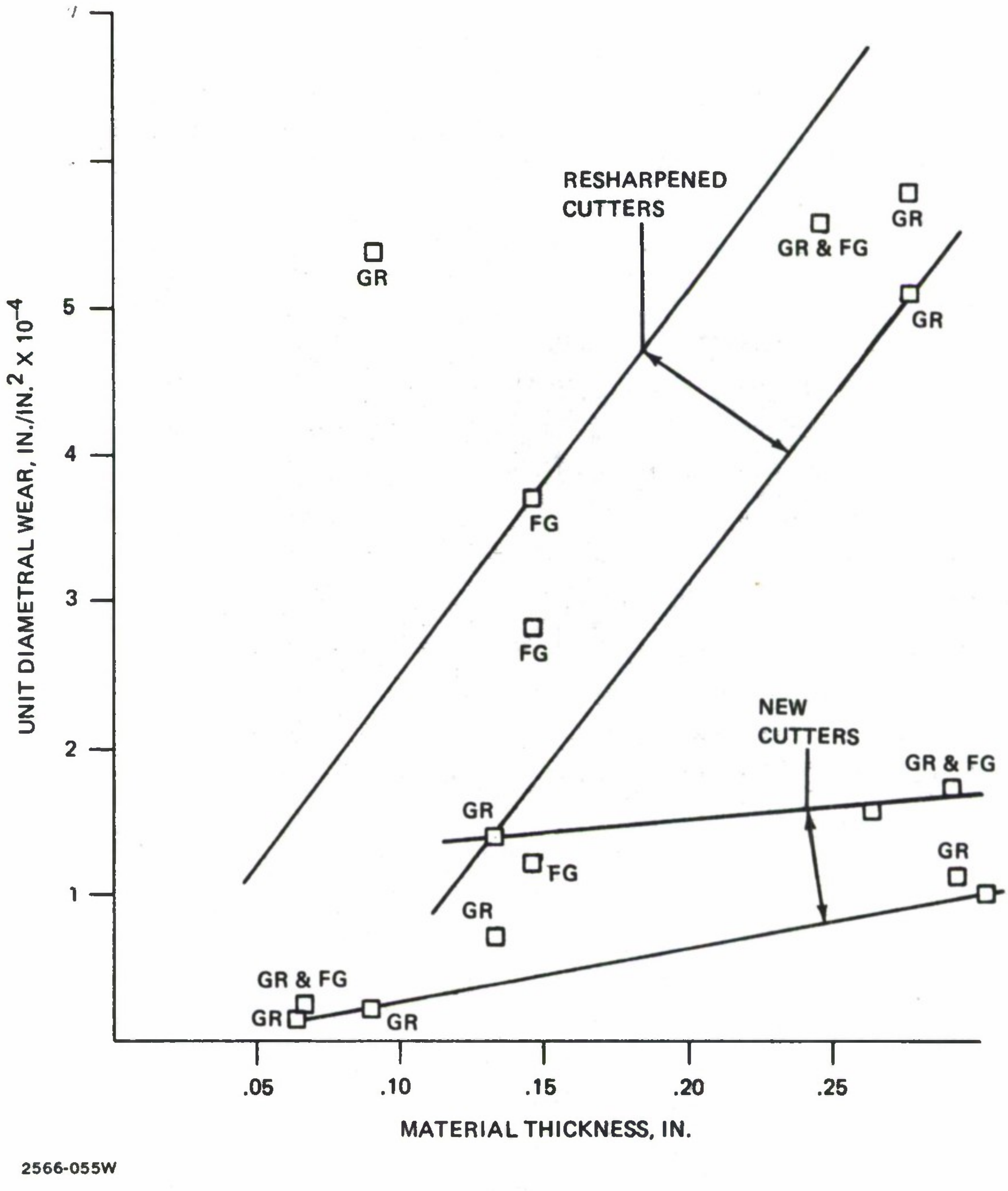


Figure 6-10 Effect of Material Thickness on Unit Wear

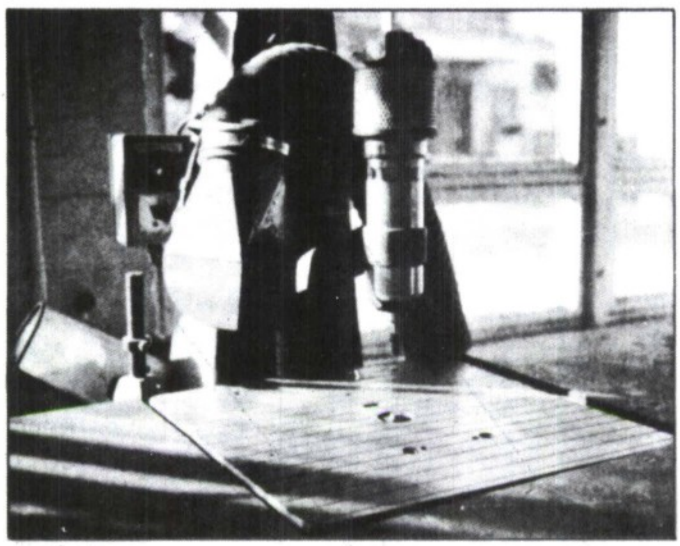


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Figure 6-11 Roto-Recipro Router

OPERATION	MATERIAL	THICK-NESS, INCH	FEED RATE, IPM	SPEED, STROKES PER MIN	DEPTH OF CUT, INCH	ROUTER BIT NO.	DIAMETRAL WEAR IN./IN.^{3} x 10^{-4}	EDGE CUT CONDITION		THRUST EFFORT REQ'D TO MAKE CUTS
								RMS	CUT QUALITY	
ROUTING	BORON/ EPOXY (B/EP)	.136	3.7	60	FULL	1	4.0	32	GOOD	AVERAGE
		.136	3.5	200	FULL	1		32	GOOD	AVERAGE
	GR/EP + B/EP (40% B/EP)	.090	8.5	60	FULL	2	25	32-63	GOOD	LOW
		.090	8.5	200	FULL	2		32-63	GOOD	LOW
	GR/EP + B/EP (40% B/EP)	.346	4.8	60	FULL	3	4.3	125	FAIR	HEAVY
		.346	5.0	200	FULL	3		125	FAIR	HEAVY
	GR/EP + B/EP (50% B/EP)	.50	3.0	200	FULL	2	1.3	125	FAIR	VERY HEAVY
TRIMMING	BORON/ EPOXY	.136	20	200	.125	2	1.3	32	GOOD	LOW
	GR/EP + B/EP (40% B/EP)	.090	20	200	.125	2		32-63	GOOD	LOW
	GR/EP + B/EP (40% B/EP)	.346	8.5	200	.125	3	0.19	125	FAIR	HEAVY
	GR/EP + B/EP (40% B/EP)	.50	8.5	200	.125	2	1.3	125	FAIR	VERY HEAVY
BEVELING	BORON/ EPOXY	.136	14	200	45° x 1/8	3	10.4	16-32	GOOD	AVERAGE
	GR/EP + B/EP (40% B/EP)	.346	16	200	45° x .200	3	0.67	16	EXCELLENT	AVERAGE
	GR/EP + B/EP (50% B/EP)	.50	15	200	45° x 1/4	3		125	FAIR	HEAVY

CONDITIONS:
- ROUTER BIT – 40-50 GRIT DIAMOND PLATED, 1/4 INCH DIAMETER.
- RPM – 13000
- RECIPROCATING STROKE – 5/8 INCH FOR ROUTING AND TRIMMING OF ALL MATERIAL THICKNESSES UP TO 1/2 INCH, 1/4 INCH FOR ROUTING AND TRIMMING OF 1/2 INCH THICK MATERIAL AND 1/2 INCH FOR BEVELING OF ALL MATERIAL THICKNESSES.
- COOLANT – HANGSTERFERS HE-2 (20-1 WATER MIX).
- SFM – 851

2566-056W

Figure 6-12 Roto-Recipro Routing, Trimming and Beveling of Cured Composites

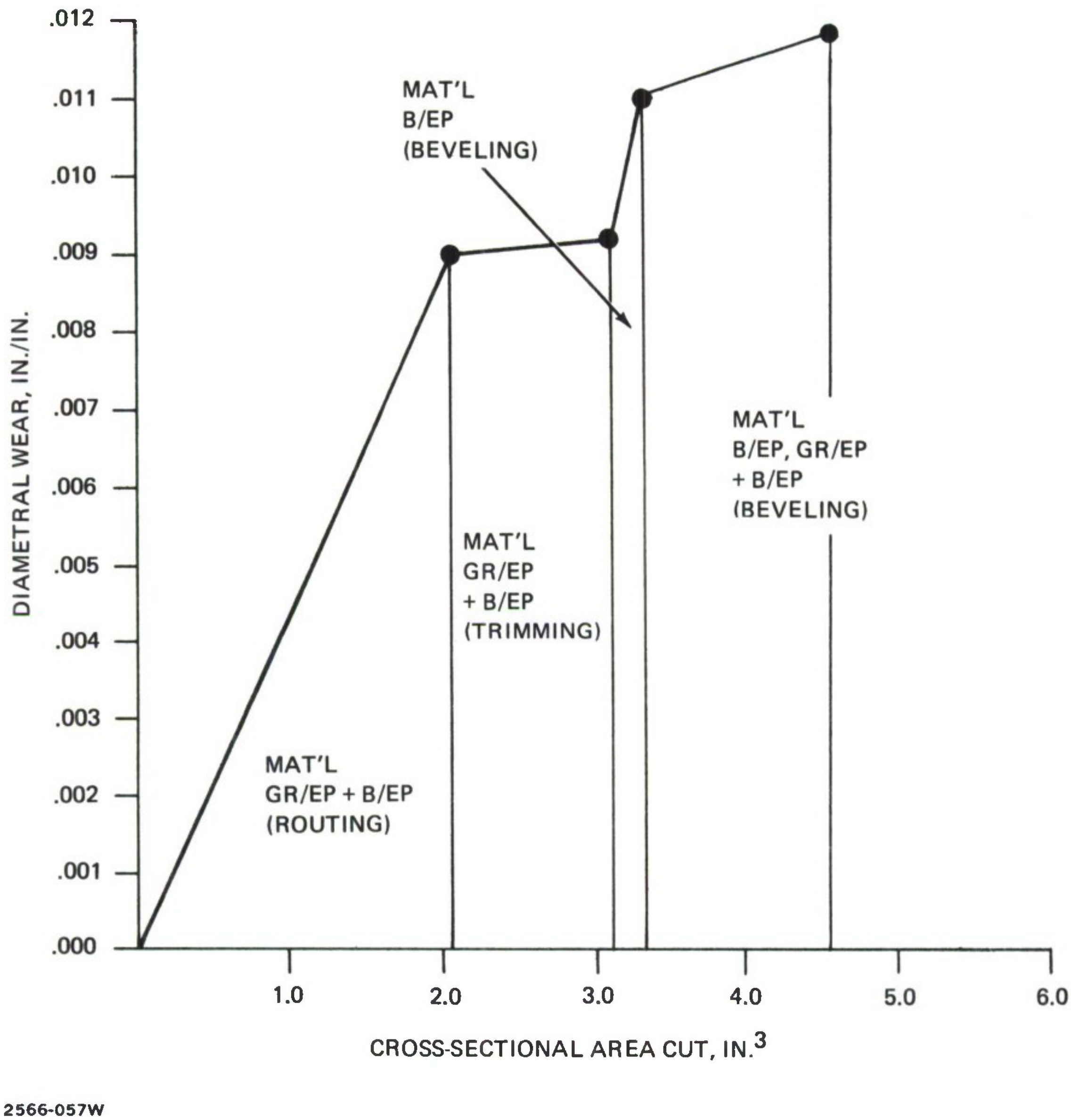

Figure 6-13 **Wear Rate for Roto-Recipro Routing, Trimming and Beveling, 40 – 50 Grit Diamond-Plated Tool (No. 3)**

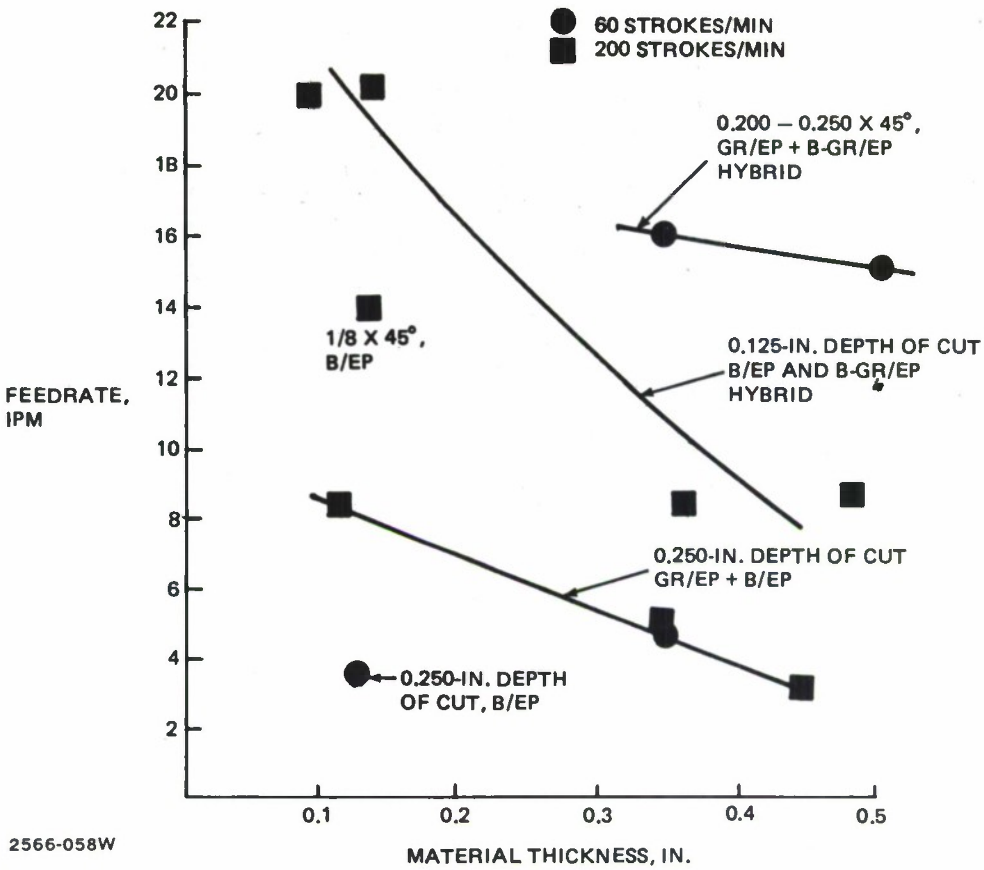

Figure 6-14 Effect of Cut Depth on Roto-Recipro Routing, Beveling and Trimming of Boron/Epoxy and Boron-Graphite/Epoxy Hybrids

MATERIAL	THICKNESS IN.	COUNTERSINKING		COUNTERBORING	
		CARBIDE	DIAMOND	CARBIDE	DIAMOND
GR/EP	1/4	D,P		P	
GR/EP + B/EP	1/2		D, U		D, U
GR/EP + KEV/EP	1/4	P		D	
GR/EP + FG/EP	1/4	P		D	
B/EP	1/8		D, U		D
KEV/EPOXY	1/8	D, P		D	
FG/EPOXY	1/8	D, P		D	

2566-059W

D – HAND DRILL MOTOR – CLECO WITH AIRCRAFT INDUSTRIES OR ZEPHYR COUNTERSINK GAGE

P – PORTABLE DRILL – DUMORE OR GARDNER – DENVER

U – ULTRASONIC DRILL MACHINE – BRANSON

Figure 6-15 Test Matrix for Countersinking and Counterboring

TEST		CUTTING TOOL			TEST NO.	EQUIP	COOLANT	RPM	FEED	NUMBER OF HOLES	RESULTS/REMARKS
MAT'L	THICK	TYPE DESCRIPTION	MAT'L	DIA							
GR/EP	.306	C'SINK Z114105 DR/C'SINK	CARBIDE	.37	48	DUMORE	NONE	1200	.0013	0	MACHINE STALLED/80 # THRUST
	.306	C'SINK Z114105 DR/C'SINK	CARBIDE	.37	50	DUMORE	NONE	2400	.002	50	.008 WEARLAND
	.300	C'SINK, PILOTED 3483-1815 421	CARBIDE	7/16	72	CLECO	NONE	2700	HAND	35	HEAVY HAND REED FORCE REQ'D APPROX .010 WEARLAND
	.300	DITTO 72	CARBIDE	7/16	73	GARDNER DENVER	NONE	21000	.002	35	.007 WEARLAND GOOD C'SINK QUALITY
	.300	C'SINK Z1141048	CARBIDE	.400	75	GARDNER DENVER	NONE	21000	.002	50	.005 CORNERWEAR GOOD C'SINK .010 LOCALIZED
	.300	C'SINK Z114105A 18° MOD	CARBIDE	.400	76	GARDNER DENVER	NONE	21000	.001	275	.005 WEARLAND
	.312	C'SINK Z114104 DR/C'SINK	CARBIDE	.37	77	DUMORE	NONE	6000	.001	125	.006 WEARLAND MOD C'SINK; 18° ALL GOOD C'SINKS
	.310	C'SINK Z114104 DR/C'SINK	CARBIDE	.37	79	M-62 SPACE-MATIC	NONE	6000	.001	107	.010 TO .012 WEARLAND ALL GOOD C'SINKS
	.310	C'SINK Z114105 DR/C'SINK	CARBIDE	.37	80	GARDNER DENVER	NONE	21000	.001	95	.006 — .007 WEARLAND ALL GOOD C'SINKS
GR & B/EP	1/2	PILOTED/PLATED 60-80 GRIT	DIAMOND	5/8	81	MANUAL	WATER	600	LIGHT-HAND	30	EXCELLENT SURFACE FINISH
	1/2	PILOTED/SINTERED 60-80 GRIT	DIAMOND	1/2	82	UMT-3	WATER	4000	1-1/4"/MIN	100-150*	EXCELLENT SURFACE FINISH
GR+KEV/EP	.275	C'SINK Z114105 DR/C'SINK	CARBIDE	.37	51	DUMORE	NONE	2400	.002	4	OUTSIDE KEVLAR LAMINATE BADLY FRAYED
GR+FG/EP	.260	C'SINK Z114105 DR/C'SINK	CARBIDE	.37	52	DUMORE	NONE	2400	.002	160	.006 WEARLAND
B/EP	1/8	PILOTED/PLATED 60-80 GRIT	DIAMOND	5/8	83	MANUAL	WATER	500	LIGHT-HAND	40	EXCELLENT SURFACE FINISH
	1/8	PILOTED/SINTERED 60-80 GRIT	DIAMOND	1/2	84	UMT-3	WATER	4000	1-1/4"/MIN	100-150*	EXCELLENT SURFACE FINISH
KEV/EP	.120	C'SINK WELDON 82°	HSS	.38	57	DUMORE	NONE	6000	.001	1	POOR C'SINK QUALITY
	.120	C'SINK WELDON 82°	HSS	.38	58	DUMORE	NONE	2400	.001	1	POOR C'SINK QUALITY
	.120	C'SINK WELDON 82°	HSS	.38	59	DUMORE	NONE	7000	.0003	1	POOR C'SINK QUALITY
	.120	C'SINK WELDON 82°	HSS	.38	61	DUMORE	NONE	2400	.002	15	SOME GOOD C'SINKS
	.120	C'SINK WELDON 100°	HSS	.50	78	CLECO OR DELTA	NONE	1350 OR 1950	HAND	307	.007 WEARLAND ALL GOOD C'SINKS
FG/EP	1/8	C'SINK Z114105 DR/C'SINK	CARBIDE	.37	53	DUMORE	NONE	2400	.002	240	.005 WEARLAND

*GRAUER, W., "ULTRASONIC MACHINING, FINAL TECHNICAL REPORT NO. AFML-TR-73-169, JULY 1973

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Figure 6-16 Summary of Countersinking Tests

6.2.1 Graphite/Epoxy and Fiberglass/Epoxy Testing

Initial testing was performed on the Dumore machine with a 3/8-inch-diameter countersink configuration that had a 5-degree form-relief angle and 3-degree axial rake. The wear-land life criterion was 0.006 inch. This tool,operated at 2,400 rpm and 0.002-inch feed, produced over 240 holes in fiberglass/epoxy, but only 160 holes in graphite/epoxy plus fiberglass/epoxy hybrid; even fewer holes, approximately 20, could be countersunk in graphite/epoxy. Similar results were obtained for graphite/epoxy, as expected, using the off-hand manual mode.

Using the same countersink configuration, tests were conducted at 21,000 rpm to establish if the trend to extended life experienced with drilling also applied to countersinking. A Gardner-Denver air-feed drill was used at 21,000 rpm and 0.002 ipr feed. Over 30 high-quality countersinks were achieved before the 0.006 wear land developed.

In order to realize a radical improvement in tool life, new countersink geometries were evaluated. The best modification found was an 18-degree form relief with a 5-degree axial rake. Subsequent tests were conducted at 21,000 rpm and 0.001 ipr. Excellent quality countersinks were obtained and tool life was extended to more than 275 holes (0.005-inch wear-land). It should be noted that these test conditions were the same as those utilized to obtain maximum drill life; therefore, an optimum combination could be achieved. The effect of speed and relief angle on the life of carbide countersinks is shown in Figure 6-17.

6.2.2 Kevlar/Epoxy Testing

Initial tests utilized unmodified carbide drill/countersinks at 0.002 ipr feed and 2400 rpm speed. Unacceptable lifting and fraying of the Kevlar/epoxy top layers occurred. The countersink design was apparently unsuited even for the thin Kevlar/ epoxy layer. This test was discontinued after four holes had been countersunk.

Several tests were conducted to evaluate the effectiveness of a Weldon 82-degree countersink with Kevlar/epoxy. Past experience and previously generated data indicated that high-speed/light-feed was best for countersinking Kevlar/epoxy. Speeds /feed rates selected for evaluation were 6000 rpm/0.001 ipr, 2400 rpm/0.001-ipr, 7000

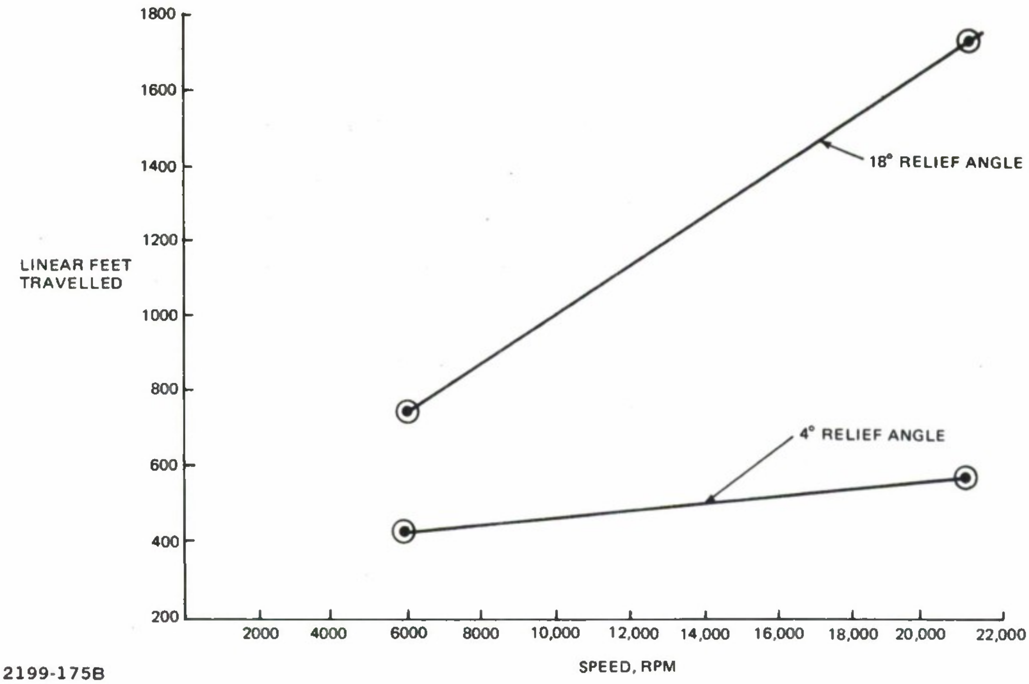

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Figure 6-17 Effect of Speed and Relief Angle on Life of Carbide Countersinks

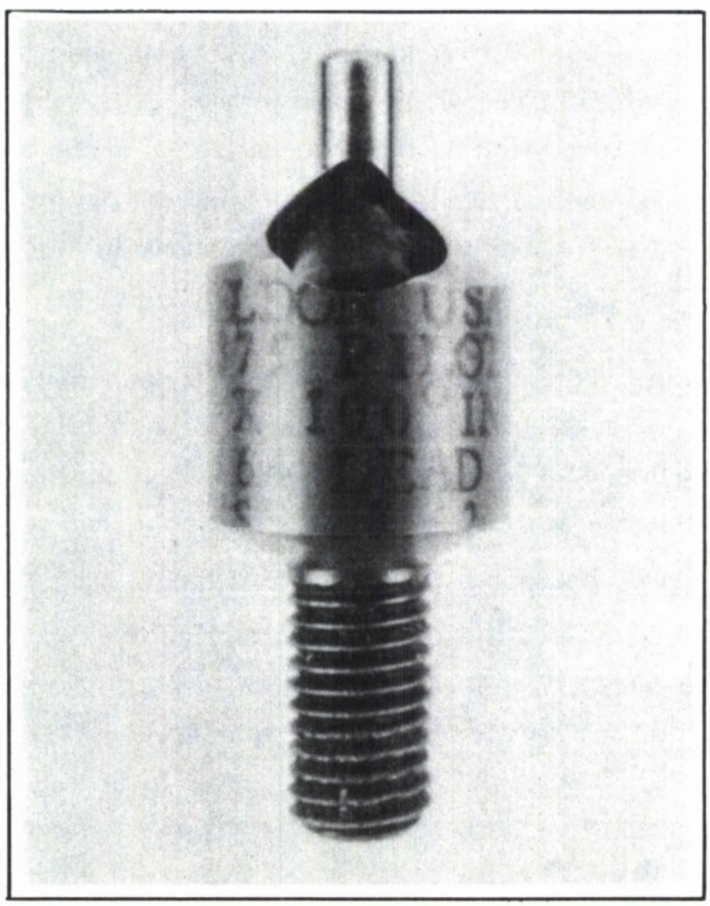

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Figure 6-18 Weldon 100-Degree Countersink (3.5x Mag)

rpm/0.0003 ipr and 2400 rpm/0.002 ipr. Light feed rates did not give satisfactory results. Best results were obtained at a speed of 2400 rpm and a feed rate of 0.002 ipr. Because this type of countersink tended to pull into the workpiece, a stop-cage was indicated to obtain best results. Using a 100-degree HSS Weldon countersink (Figure 6-18) with a countersink-cage and an air motor or a drill press at 1350 and 1950 rpm produced 307 good countersinks.

6.2.3 Boron/Epoxy and Graphite/Epoxy Hybrids

Diamond-plated and diamond-sintered countersinks were evaluated at various speeds and feeds. Off-hand countersinking tests were performed with a Cleco manual drill motor having a stop countersink. Ultrasonic countersinking tests were performed with a Branson Model UMT-3 drilling machine. Plated countersinks were used with the hand drill motor; sintered diamond tools were used with the ultrasonic drilling machine. The materials evaluated included boron/epoxy and boron/epoxy-plus-graphite/epoxy hybrid containing 50 percent of each type of material (Reference 10).

Because feed rate has a pronounced effect on diamond tool life, low feed rates are recommended to maximize tool life. The plated countersinks become totally worn when the exposed diamonds (0.006-inch exposed depth) become worn flat; cutting is then accomplished with a great deal of effort. Ultrasonic countersinking tests on boron/epoxy and hybrids thereof showed that angular wear on sintered diamond tools becomes excessive after 100 holes have been countersunk. Although the amount of wear on the countersink itself is slight, the angular change approaches the maximum a allowable, countersink-angle tolerance. The pilots on both types of countersinks wear quite rapidly when boron fibers are cut. The pilot in the plated tool is replaceable; the pilot in the sintered tool can be refurbished by nickel plating. Although plated tools wore more rapidly than sintered tools, their lower acquisition cost makes plated countersinks more cost-effective. Because of the relatively short life of sintered countersinks, it is recommended that a rough countersink be made first with a 40- to 60-grit tool and a secondary finishing operation be made with a 60- to 80-grit tool.

6.3 COUNTERBORING

The objective of this task was to optimize the parameters to counterbore cured composite laminates. Criteria such as ease of operation, tolerance achieved, reproducibility, surface finish, tool wear and speed were assessed to establish the best method of operation. The materials used in this task included graphite/epoxy, boron/epoxy, Kevlar/epoxy, fiberglass/epoxy and hybrids thereof. The test matrix is shown in Figure 6-14.

6.3.1 Cutting Tools and Equipment

Analysis of the results of the tests to optimize the machining parameters indicated that the most efficient cutting tool materials were diamond for boron/epoxy and hybrids thereof, and carbide for the rest of the materials listed in Figure 6-15. The hand drill motors used during these tests were standard air-driven Cleco types with Aircraft Industries stop countersinks. The Dumore unit, which has an air-over-oil feed system, was used when portable machining was required. The Dumore drilling machine was used to simulate the Winslow Spacematic portable unit because it has the same feed system and readily available feeds and speeds.

6.3.2 Tool Wear

Measurements of the wear land (amount of erosion on the cutting lip surface--not that which is worn away) of the carbide cutting tools were taken at the cutting edges about two-thirds of the distance from the center to periphery. The tool life criterion was a maximum 0.006-inch wear land development. In the case of the diamond-sintered tools, wear was determined by the amount of eroded diamonds. The diamond-plated tools were considered completely worn when the tools ceased removing material, and when the time and effort for hand tools became excessive.

6.3.3 Recommended Parameters

The optimum parameters for counterboring the selected materials are shown in Figure 6-19. In general, only a few counterbores can be made per tool, since the entire cutting edge bears on the workpiece material during the entire operation. Torque and thrust forces are three times that for countersinking of graphite/epoxy. Thrust values rose to over 60 pounds after a few holes had been counterbored. This operation became very difficult to accomplish in a manual mode and accelerated the amount of tool wear.

MATERIAL	PERCENT GR/EP	THICKNESS, IN.	C'BORE TOOL		TEST NO.	EQUIP-MENT	COOLANT	SPEED, RPM	FEED, IPR	NUMBER OF C'BORES	DEPTH OF C'BORE INCH	MAT'L REMOVED, INCH³	C'BORE SURFACE FINISH	WEAR, INCH
			TYPE	DIA., IN.										
GRAPHITE/EPOXY	100	0.270	CARBIDE TIPPED 3 FLUTES	9/18	56	PORTABLE MODE (DUMORE)	NO	4800	0.005	5	0.180	0.22	EXCELLENT	0.006 ①
GRAPHITE/EPOXY PLUS BORON/ EPOXY	50	0.530	DIAMOND PLATED 40 - 50 GRIT	0.850	85	HAND DRILL MOTOR	HANGSTERFERS HE-2 (20-1) MIX	500	MEDIUM HAND	15	0.168	0.83	EXCELLENT	100% WORN (.006)
GRAPHITE/EPOXY PLUS BORON/ EPOXY	50	0.510	DIAMOND SINTERED 60-80 GRIT	0.650	86	BRANSON UMT-3	WATER	4000	1.0 INCH/ MIN (0.04 IPM ACTUAL)	27	0.202	2.0	EXCELLENT	.0018
GRAPHITE/EPOXY PLUS KEVLAR/ EPOXY	71	0.275	CARBIDE TIPPED 3 FLUTES	9/18	63	PORTABLE MODE (DUMORE)	NONE	3600	0.001	45	0.125	1.40	GOOD	0.006 ①
GRAPHITE/EPOXY PLUS FIBER GLASS/EPOXY	71	0.250	CARBIDE TIPPED 3 FLUTES	9/18	62	PORTABLE MODE (DUMORE)	NONE	3600	0.001	25	0.126	0.82	EXCELLENT	0.006 ①
BORON/EPOXY	0	0.137	DIAMOND PLATED 40 - 50 GRIT	0.650	67	HAND DRILL MOTOR	HANGSTERFERS HE-2 (20-1) MIX	500	MEDIUM-HAND	36	0.115	1.37	EXCELLENT	100% WORN (.006)
KEVLAR/EPOXY	0	0.103	CARBIDE TIPPED 3 FLUTES	9/18	66	PORTABLE MODE (DUMORE)	NONE	6000	0.0006	2	0.125	0.06	FAIR	NO READING
FIBERGLASS/ EPOXY	0	0.145	CARBIDE TIPPED 3 FLUTES	9/16	64	PORTABLE MODE (DUMORE)	NONE	3600	0.001	113	0.100	2.81	EXCELLENT	0.006 ①

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NOTE: ① WEARLAND DEVELOPMENT

Figure 6-19 Summary of Recommended Counterboring (Spot Facing) Parameters

Unacceptable lifting and fraying of the top laminate layers occurred during counterboring of the Kevlar/epoxy specimens. Analysis of the test results indicated that a new cutter geometry is required. Counterboring of Kevlar/epoxy-plus-graphite/epoxy laminates could be accomplished more readily, although the top layer still frayed. Good hole finishes were obtained when cutting through the graphite/epoxy layers, apparently due to a polishing action by the Kevlar fibers. Sanding of the top surface with wet 400-grit paper will provide an acceptable surface finish. Although diamond tools provide excellent counterbores with boron/epoxy and hybrids thereof, the high thrust loads limit the number of counterbores that can be obtained. Dimensional tolerance and depth reproducibility are within plus or minus 0.020 inch for all cases, since the equipment used had mechanical stops.

Section 7

NON-DESTRUCTIVE EVALUATION

The objective of this phase was to establish a low-cost inspection system and a comprehensive guide for the proper selection and use of NDE to detect damage induced by cutting, machining, and drilling. Each practical processing technique and material combination were analyzed to determine the type and extent of damage that can occur. All possible NDE techniques applicable to these requirements were evaluated to permit the selection of the most promising ones (relating to sensitivity and costs) for further experimental studies. Correlations with destructive analyses were then performed to fully characterize the capabilities of the NDE techniques and facilitate the selection of the most optimum one(s). The final technique was then developed into a rapid low-cost system using automation and integrated into the manufacturing process.

7.1 TASK 1 - NDE TECHNIQUE SCREENING

The criteria for selecting the nondestructive evaluation methods for use in evaluating drilled, machined and cut composite surfaces included speed of application, cost, ease of clean-up, effectiveness and applicability to automation. Some of the methods, though effective in detecting flaws or anomalies in composite edges or holes, didnot lend themselves to the other criteria mentioned above and established by the initial proposal. Consequently, these methods were relegated a lesser value in the overall selection of the most appropriate nondestructive evaluation procedure.

The various nondestructive methods investigated are listed in Figure 7-1. They have been graded as to their effectiveness, when compared to the overall criteria required by the program, on a scale of one through ten(one being the lowest grade and ten being the highest qualified or most successful NDE method). Selection of the best methods was based on the results of the tests performed under this program, Grumman experience through the past several years of working with composites, the damage tolerance program for the B-1 composite horizontal

METHOD NO.	TYPE	RATING (10 IS HIGHEST VALUE)									
		1	2	3	4	5	6	7	8	9	10
1.	ULTRASONICS – RESONANCE						X				
2.	ULTRASONICS – CONVENTIONAL					X					
3.	ULTRASONIC SPECTROSCOPY		X								
4.	HARMONIC BOND TESTING		X								
5.	PENETRANT – CONVENTIONAL				X						
6.	VIDEO SCANNING*				X						
7.	RADIOGRAPHY – IMAGE ENHANCEMENT		X								
8.	RADIOGRAPHY – TRACER								X		
9.	FLUOROSCOPY – TRACER									X	
10.	INFRA RED SCANNING			X							
11.	LIQUID CRYSTALS		X								
12.	BORESCOPE/FIBEROPTICS					X					
13.	ENHANCED VISUAL		X								
14.	MICROWAVES		X								
15.	TRACER – FLUORESCOPY ENHANCED										X

*VERY EFFECTIVE FOR BREAKOUT DETECTION

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Figure 7-1 Rating of NDE Methods for Composite Flaw Detection

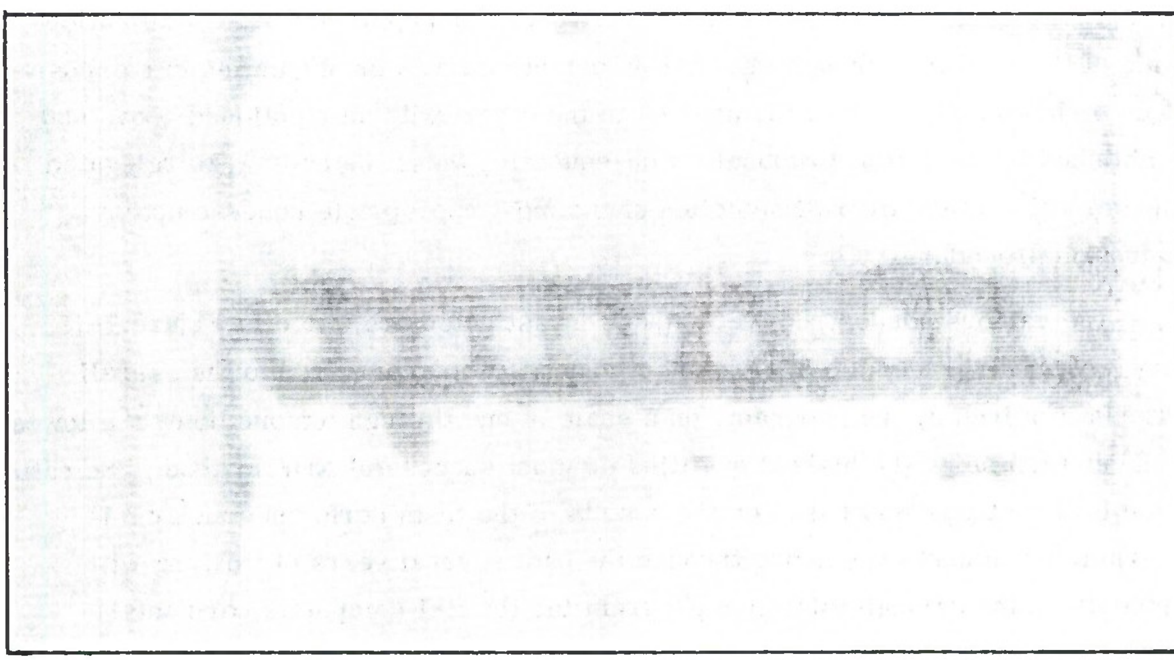

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Figure 7-2 Ultrasonic "C" Scan of Graphite/Epoxy plus Kevlar/Epoxy Composite Showing Delamination Around Each Hole

stabilizer and the Advanced Development of Conceptual Hardware - Horizontal Stabilizer program (References 11 and 12). Evaluation of the various methods showed that a combination of several methods was the best for optimum flaw detection.

7.1.1 Ultrasonics - Resonance

The instrument generally used for transducer resonance of composites is the Fokker Bond Tester. Holes were examined using a 3/8-inch diameter transducer. Only delaminations greater than 1/4-inch could be reliably detected. Since delaminations and flaws smaller than 1/4 inch can be easily detected by other methods, ultrasonic resonance was judged not applicable.

7.1.2 Ultrasonics - Conventional (Pulse-Echo and Through Transmission)

In order to automate a conventional ultrasonic system with existing drilling fixtures, a water-squirter system would have had to be utilized. Development of this technique would have been costly and require expensive water supply and drainage facilities. Though effective in detecting delaminations in composites (see Figure 7-2), the possible entrapment of water in edge delaminations (thereby reducing sensitivity) and the difficulty in establishing a portable squirter system significantly reduced the probability of using conventional ultrasonics.

7.1.3 Ultrasonic Spectroscopy

This method relies upon the theory that certain flaws in composites cause characteristic ultrasonic frequencies when subjected to ultrasonic waves. The method has not yet proved itself to be sufficiently reliable for use on routine composite evaluation programs.

7.1.4 Harmonic Bond Testing (with Mechanical Excitation)

Harmonic bond testing is generally limited to metallic parts, though nonmetallic probes can detect delaminations 1-1/4 x 1 inch in size or larger. Since this minimum size is larger than that which other methods can detect, the method does not have the sensitivity needed for composite edge and hole flaw detection.

7.1.5 Penetrant (Conventional Dye and Fluorescence)

The successful use of conventional dye and fluorescent penetrant as a method for hole and edge flaw detection has not been consistent. The best results were obtained by using a water-washable developer, Uresco P-232D (see Figure 7-3). This penetrant is visible as a red contrast and when exposed to ultraviolet light exhibits an orange/red fluorescent glow. A self-drying developer (Uresco D-495D) was used with K-410 solvent remover. Although this method found virtually all delaminations and cracks, it exhibited a very high degree of sensitivity. Attempts were made to reduce the sensitivity of the system through experienced interpretation, but results were highly subjective. Cuts or gouges from machining or drilling were constantly detected giving rise to many false positive flaws. Because the depth of the flaw in the composite could not be accurately estimated by penetrant inspection, its relationship to size allowables could not be estimated, reducing its effectiveness as a viable method. Post-inspection cleaning operations also detracted from the method's acceptance as a real-time integrated system. Consequently, penetrant inspection was not selected as the primary method to fulfill the intent of this program.

7.1.6 Video Scanning

The use of video scanning by itself as the sole criterion for edge flaw detection is not sufficient. The method is effective for rapid examination of the composite edge or hole to detect obvious breakout damage or major delamination. Its application would be most advantageous when used in combination with other methods of edge flaw detection. The main problem associated with looking directly at the edge of a composite via video scanning is interpretation of flaw indication. For example, it is difficult to differentiate cracks from delaminations or fiber pullout; consequently video scanning can result in finding false positives. Video scanning can also overlook fiber breakout which remains tightly in place and appears visually sound, resulting in false negative indications (see Figure 7-4). The method does lend itself to an automated system and when used with other methods becomes an effective tool for composite inspection.

7.1.7 Radiography

In order for radiography to be effective with composites for delamination or crack detection, the separation between the material should be at least two percent. Because most edge and hole delaminations remain tight, there is not sufficient distance between flawed surfaces to be detected by radiography. By itself, radiography does not offer a sensitive method for use with composites. Other

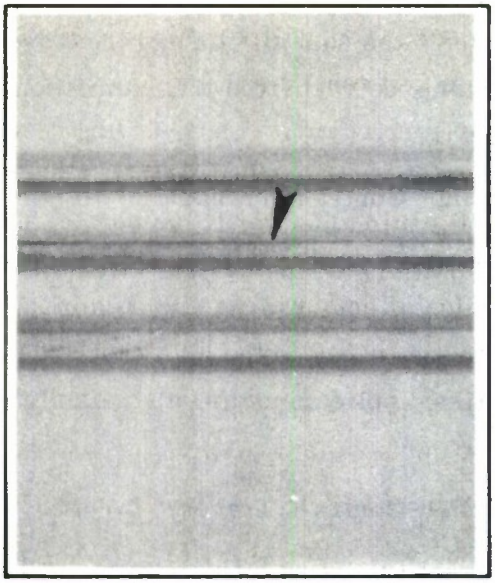

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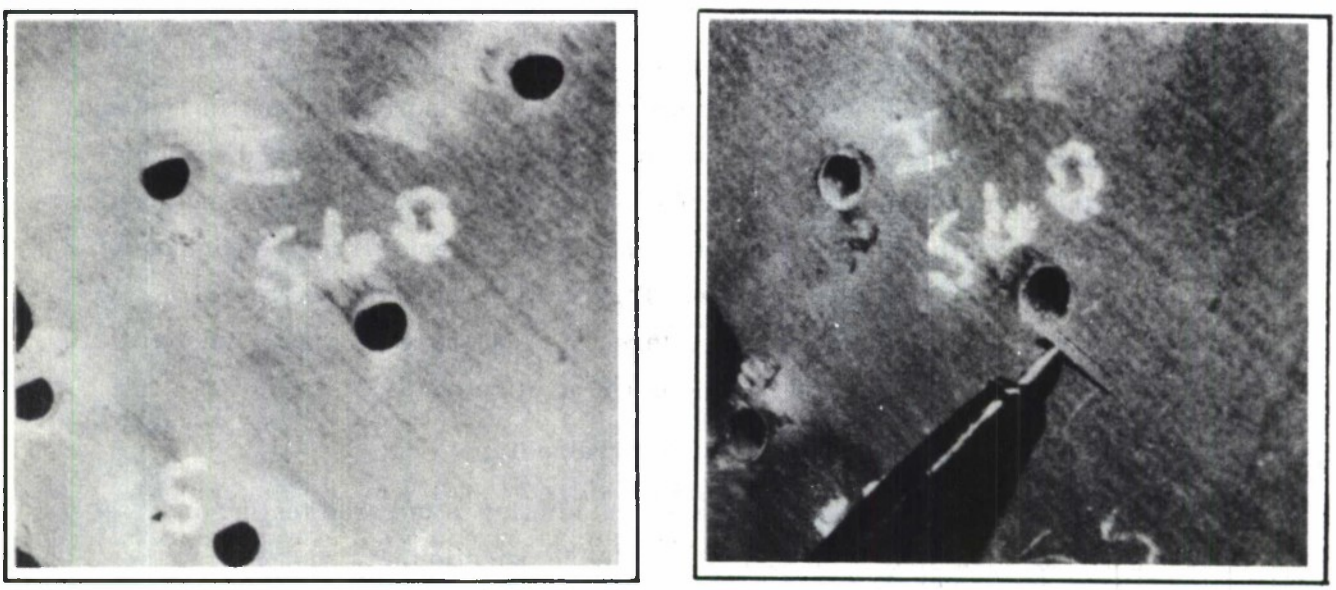
Figure 7-3 Delamination in Band-Sawed Kevlar/Epoxy Revealed by Dye Penetrant



a. Visually Acceptable Hole as Determined by Initial Video Scanning

b. Fiber Breakout on Same Hole as Observed After Detection by Other NDE Method

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Figure 7-4 Fiber Breakout Overlooked by Initial Visual and Video Scanning Method problems with radiography are the cost of film and the time lag for processing the film. These last two problems detract from the automation aspect of the application and present a high cost factor.

7.1.8 Radiography (with High-Contrast Tracer)

High-contrast tracers have proved to be a very effective method when used with radiography for detection of edge cracks and delaminations in composites. The drawback of using radiographic traces is the high cost and preparation of the radiographic film. Real-time applications are also significantly diminished because of the processing time lag.

7.1.9 Fluoroscopy (with High-Contrast Tracer)

The use of high-contrast traces with fluoroscopy appears to be the most promising method developed to date. When combined with edge enhancement and video scanning, the concept lends itself well to an automated real-time composite edge and hole evaluation system.

7.1.10 Infrared Scanning

The use of infrared scanning has met with some success in the industry. Several problems associated with using infrared scanning for composite edge and hole evaluation have made the method not as effective as it had been in other applications. As the thickness of the composite material increases, the time to heat the panels also increased. Time then becomes a factor in using infrared scanning and affects the cost of the method. When scanning along composite edges and inside holes, the heat from the generation source enters the material from the composite skin side and from the hole or part edge. This multidirectional heat transfer situation poses a problem because heat enters the area where it is not wanted and masks the flaw. As a result, the method is not as effective as desired.

7.1.11 Liquid Crystals (Encapsulated in Removable Tape)

The liquid crystal approach has problems similar to infrared testing and consequently does not lend itself to a fast, reliable detection.

7.1.12 Borescope/Fiberoptics

An Olympus 90-degree borescope was used to examine the holes. It was necessary to manipulate the scope in order to view the entire hole surface, thereby increasing inspection time. Interpretation was very subjective. The difficulty of interpreting the indications was due to the presence of minor tool marks and resin tearout. The examination was performed in the laboratory and took approximately three minutes per hole. More experience with this type of inspection technique would result in improved interpretation and reduced inspection time. However, this technique was judged unreliable because of the many false positive indications obtained and excessive inspection time. The depth of the flaw also could not be estimated. Similar difficulties were obtained when white light and 10X magnification were used.

7.1.13 Enhanced Visual

The enhanced visual method involved problems similar to those encountered in video scanning. Although edge enhancement of the display made some of the flaws more pronounced, flaw depth perception was still difficult to ascertain.

7.1.14 Microwaves

Some progress has been made with the use of microwaves in composite flaw detection. The application has been most effective with composites that have flaws within the structure away from significant geometry changes. Because of its geometry sensitivity, microwave evaluation of composite edges and holes has not been effective and does not lend itself well to the criteria of this program.

7.1.15 Tracer-Fluoroscopy Enhanced

The use of a radio-opaque tracer, which is drawn into cracks of delaminations found at the edges of cut composites or in drilled holes, is the most promising of the NDE methods when combined with a real-time fluoroscopy system. The combination of tracer, fluoroscopy and subsequent image enhancement offers the best approach for detecting cracks and delaminations, on a routine automated basis. The use of fluoroscopy eliminates costly X-ray film processing problems and lends itself well to an automated real time inspection system. Clean-up is virtually non-existent as most material evaporates in 24 hours. Permanent records may be maintained on a video tape recorder system.

7.2 TASK 2 - SELECTION/EVALUATION OF OPTIMUM NDE METHODS

Techniques from the Task 1 screening effort were evaluated using specimens generated by cutting, machining and drilling. An optimum technique was selected and used to categorize edge quality of typically processed specimens.

7.2.1 NDE Selection

Selection of the optimum NDE methods for evaluation of composite edges and holes is based upon several important considerations. First and foremost are the design requirements and applications of the composite structure. For example, during the damage tolerance program for the B-1 composite horizontal stabilizer (Reference 9), the types of defects induced in the specimens consisted of delaminations or voids 1/2 x 1/2 inch, scratches (2 plies deep), radius voids (0.050 x 8-inch maximum) and fiber breakout from drilling holes. All flaw sizes were large enough to permit ultrasonic detection with 90 percent probability and 95 percent confidence. The results of these tests showed that all flawed components, with two exceptions, successfully passed two lives of fatigue. Neither of the flawed component failures was attributed to the programmed flaws placed into the specimen, and none of the flaws caused any perceptible reduction in strength of the specimens. In these tests, the specimens (which were actual production parts or close representations) were designed with flaws that could reliably be detected by conventional means. The selection of NDE methods should then be a function of the part design and corresponding flaw size allowables. Designs should be such that allowable flaw sizes be large enough to be detected with a high degree of confidence. Other consideration for selecting NDE methods are cost, time to use, clean-up considerations, and automation requirements.

The NDE methods selected from those evaluated and integrated into an automated system with the Grumman Five-Axis Drilling Fixture are video scanning and tracer-fluoroscopy with image edge enhancement. The Five-Axis Drilling System has the ability to position a processing unit at a predetermined location on curved as well as flat surfaces. Two other methods, dye penetrant and fiberoptics/boroscopy, are also recommended in the event that small flaws such as microcracks and fiber/resin pullout must be detected as part of engineering design requirements. These two methods are effective but costly in time and materials.

Figure 7-5 lists the several types of flaws that may occur as a result of cutting, drilling and machining composites. Shown are the materials tested and the corresponding NDE methods recommended to detect and locate the flaws. The five flaw classifications are:

- Delamination - a separation between plies as a result of internal stresses caused by machining, drilling or cutting operations. Delaminations may occur in the entrance side, exit side, or within the composites.
- Breakout - a splintering effect, usually on the exit side of a drilling or cutting operation. The breakout may be one or several plies thick.
- Microcrack - intra-laminar cracks usually running parallel to the cutting direction or ply direction. These cracks can range from 0.001 to 0.400 inch in length and are some times difficult to detect visually. Occasionally these cracks may run perpendicular to the cutting direction.
- Fiber/Resin Pullout- very small pieces of resin or composite fibers pulled away from the matrix as a result of the cutting or drilling operations.
- Shredding - tearing of one or more composite plies as a result of forces pulling material away from the composite. The problem is most prevelant in Kevlar-type materials and occurs predominantly in the top or bottom plies.

When selecting NDE methods, care should be taken to avoid using too many methods, since cost may be a predominant factor in a composite inspection program.

7.2.2 NDE Technique Evaluation

The nondestructive evaluation techniques screened from Task I required evaluation as to their effectiveness and reliability in detecting the several flaw types identified previously as being characteristic of composites. The initial effort was to determine which sizes of these flaws were acceptable or rejectable and conduct probability studies as to the confidence with which these flaws could be detected. The critical flaw sizes were to be taken from the B-1 Effects of Defects Program and utilized in this program. Ten specimens with marginally rejectable flaws and five specimens with marginally acceptable flaws were to be evaluated three times each. The results of the damage tolerance program showed flaws of a relatively large size

		PHASE I				PHASE II	PHASE III				PHASE IV			
		CUTTING				DRILLING	MACHINING				NONDESTRUCTIVE EVALUATION METHOD			
MATERIAL	DAMAGE	RADIAL SAW	BAND SAW	WATER JET	HAND RADIAL SAW	DRILLING	HAND ROUT	COUNTER SINK	HAND TRIM	COUNTER BORE	TRACER FLUOROSCOPY	DYE PENETRANT	FIBER OPTICS/ BOROSCOPE	VIDEO SCAN
GRAPHITE/EPOXY KEVLAR/EPOXY	DE-LAMINATION			X	X		X	X	X		X			X
	BREAKOUT		X								X			X
	MICRO-CRACKS						X				X	X	X	
	FIBER/RESIN PULLOUT													
	SHREDDING			X	X		X	X		X				X
FIBERGLASS/ EPOXY	DE-LAMINATION							X		X	X			X
	BREAKOUT													
	MICRO-CRACKS													
	FIBER/RESIN PULLOUT													
	SHREDDING													
GRAPHITE/ EPOXY& FIBERGLASS/ EPOXY	DE-LAMINATION		X	X	X		X			X	X			X
	BREAKOUT		X								X			
	MICRO-CRACKS		X								X	X	X	
	FIBER/RESIN PULLOUT		X	X							X		X	
	SHREDDING			X										X
GRAPHITE/EPOXY	DE-LAMINATION			X		X	X				X			X
	BREAKOUT	X	X			X	X				X			X
	MICRO-CRACKS		X								X	X	X	
	FIBER/RESIN PULLOUT	X				X					X		X	
	SHREDDING													

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(1/2)

Figure 7-5 Induced Flaws and NDE Detection Methods (Sheet 1 of 2)

		PHASE I				PHASE II	PHASE III				PHASE IV			
		CUTTING				DRILLING	MACHINING				NONDESTRUCTIVE EVALUATION METHOD			
MATERIAL	DAMAGE	RADIAL SAW	BAND SAW	WATER JET	HAND RADIAL SAW	DRILLING	HAND ROUT	COUNTER SINK	HAND TRIM	COUNTER BORE	TRACER FLUOROSCOPY	DYE PENETRANT	FIBER OPTICS/ BOROSCOPE	VIDEO SCAN
GRAPHITE/EPOXY & BORON/ EPOXY	DE-LAMINATION		X	X		X					X			X
	BREAKOUT	X				X					X			X
	MICRO-CRACKS			X							X	X	X	
	FIBER/RESIN PULLOUT	X	X	X		X					X		X	
	SHREDDING													
BORON/EPOXY	DE-LAMINATION			X							X			X
	BREAKOUT	X	X								X			
	MICRO-CRACKS													
	FIBER/RESIN PULLOUT	X									X		X	
	SHREDDING													
KEVLAR/ EPOXY	DE-LAMINATION		X		X	X		X	X		X			X
	BREAKOUT					X					X			
	MICRO-CRACKS													
	FIBER/RESIN PULLOUT													
	SHREDDING				X	X		X						X

2566-063W
(2/2)

Figure 7-5 Induced Flaws and NDE Detection Methods (Sheet 2 of 2)

(1/2 x 1/2-in. delamination) could be tolerated by the composite designs of that program. Most of the flaws generated by the cutting, drilling and machining operations of this program were significantly smaller than those established in the damage tolerance tests. Consequently, based on the design criteria of the damage tolerance program, most of the generated flaws for the present program would be judged acceptable. Since flaw acceptance criteria vary from design to design, it was decided to evaluate the selected techniques on the merits of the NDE method to reliably detect any flaw which could be observed visually or by micro-section. Probability and confidence levels would be calculated on successive detection of the same kind of flaw for each material or operation.

The specimens generated by the cutting, drilling and machining phases were evaluated by several NDE methods selected from these initially proposed for screening. The methods -- tracer-radiography enhanced, dye penetrant, stereoscope-boroscope and microsectioning, were used in accordance with the Quality Assurance Specimen Evaluation Logic Diagram (Figure 7-6). Specimens were initially evaluated visually and then subjected to stereoscope or borescope inspection. After visual and optical review, the specimens were tracer-radiographed using 1,4 diiodobutane $I(CH_2)_4I$. This liquid (specific gravity of 2.3) is very effective for absorption of X-radiation, evaporates easily and quickly, and is not especially hazardous. Although it is compatible with composites used on this program, some reaction with sealants has been noted.

7.2.2.1 Tracer Application. The tracer liquid is applied to the composite edge or hole (see Figure 7-7) and allowed to penetrate the flawed area for approximately two minutes. Excess DIB on the specimen surface should be cleaned off prior to radiography so as to avoid false positive indications. The use of tracer radiography is a very informative techinque, since it not only identifies the presence of a flaw, but also determines the depth or extent of a crack or material delamination (Figure 7-8). The distance "d" or depth in Figure 7-8 measures the maximum extension of the delamination from the cut edge of drilled hole into the composite, and is the standard nomenclature used throughout the report. Figure 7-9a shows a tracer radiograph of a drilled hole in a graphite/epoxy laminate. The tracer liquid, DIB, is seen in white outlining the delamination around the upper part of the hole. Figure 7-9b shows a 2X magnification of the hole using image edge enhancement. Notice how the outline of the delamination is more clearly marked, lending edge enhancement for effective use with computer pattern recognition programs.

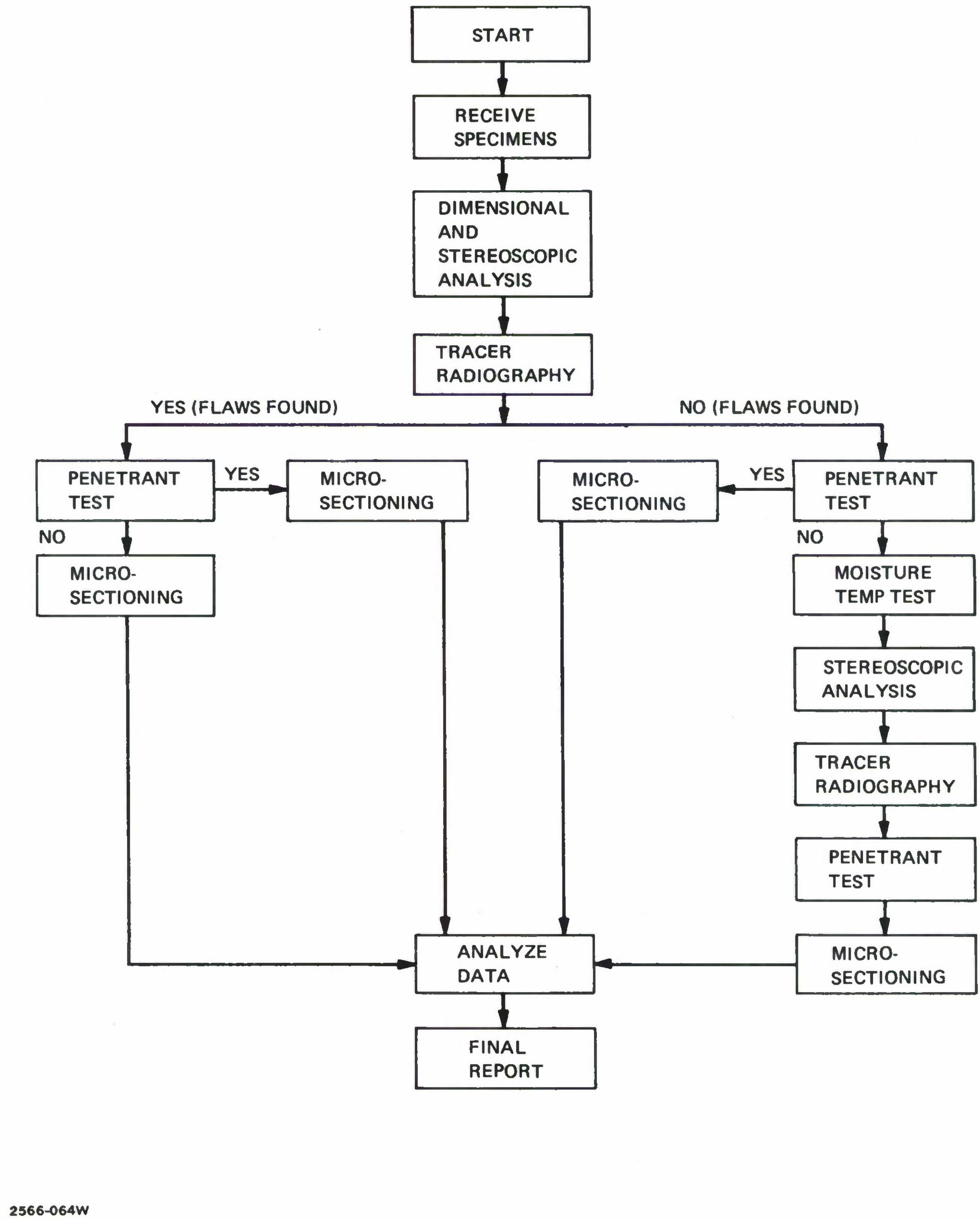

Figure 7-6 Quality Assurance Specimen Evaluation Logic Diagram

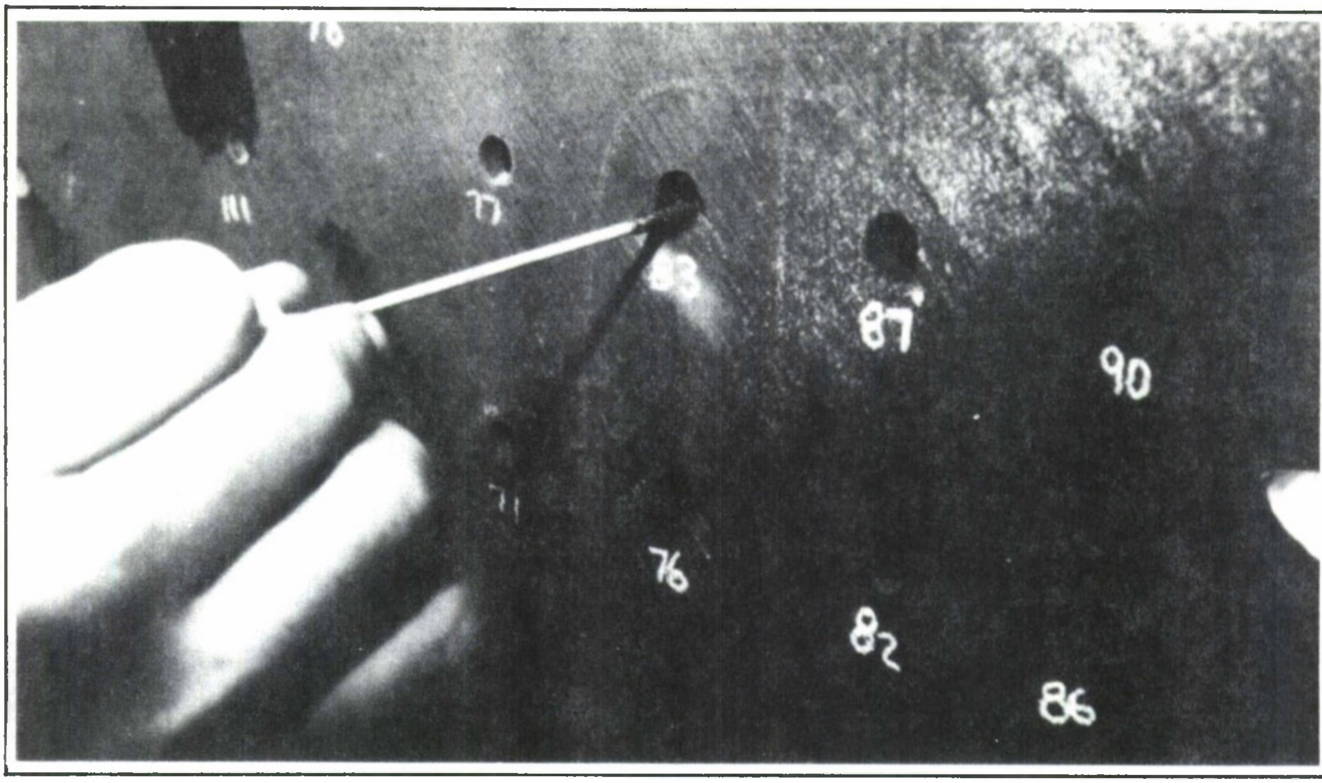

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Figure 7-7 Application of DIB Radiographic Tracer to Composite Hole

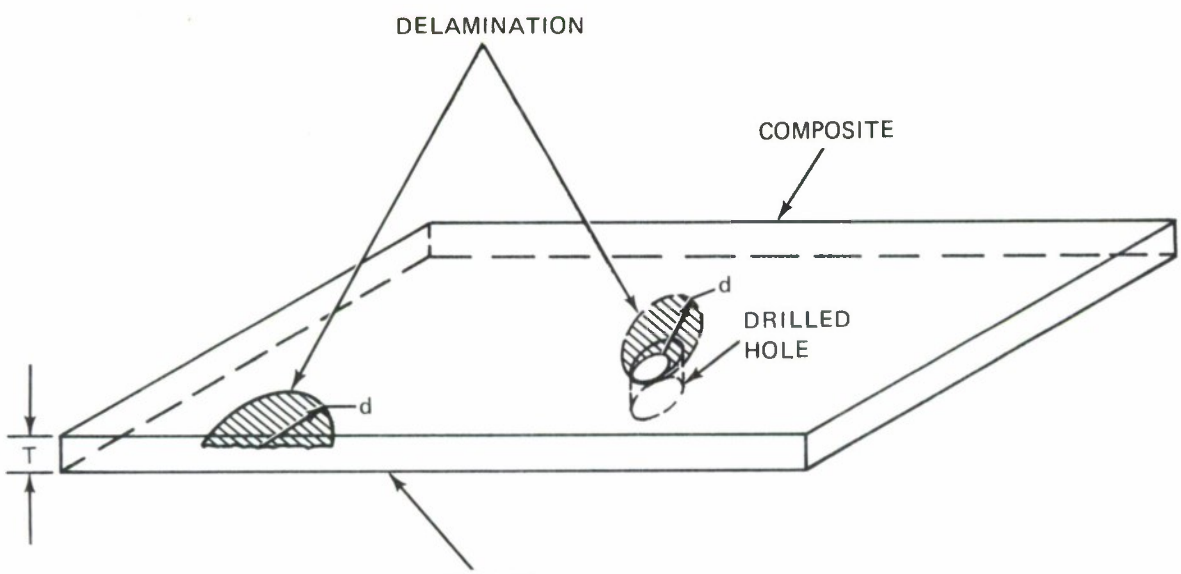

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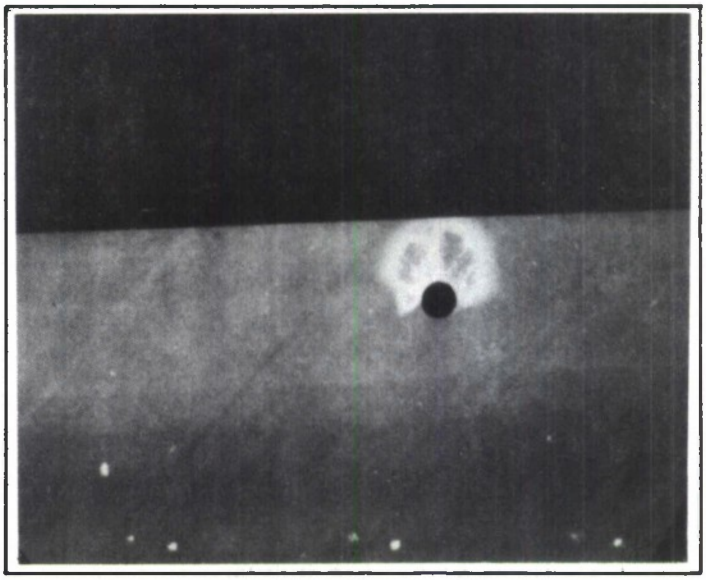
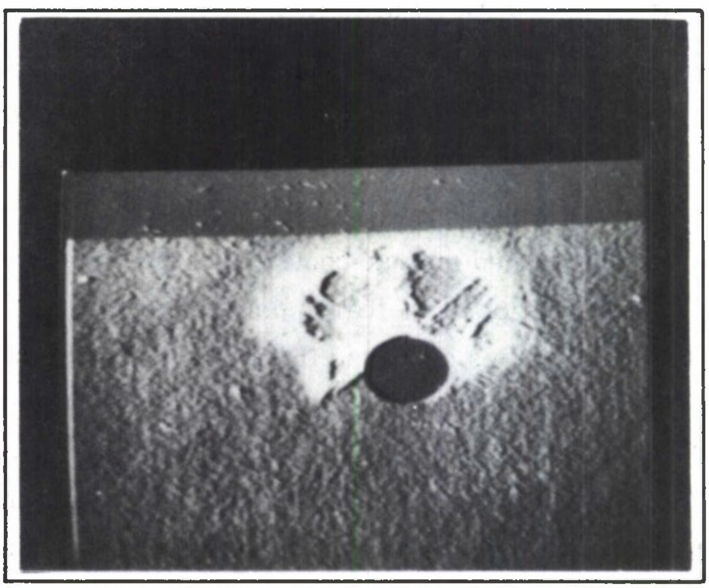
Figure 7-8 Composite Material with Delaminations from Cut Edge and Drilled Hole



a. White Outline of Delamination by DIB Tracer (1X Magnification)



b. Edge Enhancement of Same Delamination (2X Magnification)

2566-065W

Figure 7-9 DIB Tracer Outlining Delamination from Drilled Hole in Graphite/Epoxy Laminate

7.2.2.2 Penetrant Application - Prior to the development of the tracer-radiography method, dye penetrant or fluorescent penetrant was one method used to identify and locate flaws open to the edge or hole of a composite. Since many penetrant systems proved difficult to clean or were too sensitive, the penetrant system used on this program consisted of a water-washable, dual-function penetrant (Uresco P-232D) and a non-aqueous developer (Uresco D-495D). The penetrant is visible as a red contrast under white light and as an orange/red fluorescent glow when subjected to long-wave ultraviolet light.

The penetrant system was used to verify findings by the tracer radiography system. For the most part all flaws found by visual and tracer radiography were verified by penetrant. The sensitivity of the penetrant system still proved very high, resulting in a high percentage of false positive penetrant indications. Minor resin/fiber pullout or rough surfaces gave false indications, leaving the method restricted to smooth and only some cutting or machining operations. Figure 7-3 shows a long delamination (dark/line) in a band-sawed Kevlar/epoxy specimen as revealed by the dye penetrant system. However, the Kevlar also absorbed some of the penetrant making interpretation very difficult at times.

7.2.2.3 Moisture Conditioning - A considerable amount of work has been performed and reported on the effect of heat and moisture on the strength of advanced composites. Hedrick and Whiteside (Reference 13) reported that moisture conditioning of laminates made from currently available boron/epoxy and graphite/epoxy materials significantly reduced matrix-controlled structural properties at elevated temperatures. No degradation of the boron or graphite fibers and only minor reductions in tensile properties occurred in moisture-conditioned specimens tested at both room and elevated temperatures. It was also reported that surface cracking in the resin at free edges can be caused by desorption moisture gradients which induce swelling stresses. As a result, different types of specimens from this program, which had been classified as good or having no appreciable amount of flaws, were conditioned at 140°F and 95 percent relative humidity for 120 days. Subsequent visual, tracer, X-ray and microsection examinations revealed no detectable micro-cracking in any of the conditioned specimens. Results of the moisture conditioning tests with bandsawed and radially sawed specimens are summarized in Figures 7-10 and 7-11.

7.2.2.4 Microsectioning - Verification of flaws located by visual, optical, tracer-radiography or penetrant was accomplished by microsectioning the specimens in the areas where other NDE methods showed the presence of flaws. Cutting of the speciments was accomplished by a silicon carbide cut-off wheel. This method of microsectioning was chosen because it had been previously demonstrated that radial type cutting caused the least flaws in a material and was less likely to cause error by creating flaws which previously did not exist during nondestructive evaluation. After sectioning, specimens were examined with calibrated binoculars and sites of flaws were measured and recorded.

7.2.3 Results of Process Evaluation

The composites evaluated were cut or machined into 1/4 to 1/2-inch-wide strips from controlled panels. The samples were identified as to material, thickness, side of specimen machined, direction of cut and other pertinent details affecting the NDE investigation. Specimens which were drilled were similarly identified.

7.2.3.1 Radial Saw - The radial saw cut specimens were the best of all the specimens cut in terms of the number and severity of flaws. Most flaws found were minor breakout and some porosity within the composite itself. Figure 7-12 shows the results of the NDE tests conducted on the specimens. No flaws were found by tracer radiography or microsectioning. Visual flaws of a superficial nature such as minor breakout and fiber pullout were, for the most part, verified by penetrant. Should design parameters require the detection of such minor flaws, only visual or penetrant methods would be successful.

The baseline in all tests for determining whether a flaw is present or not is the microsectioning method with some verification by visual means. Hence, in the radial saw specimens the tracer-radiography method showed that 18 of 18 specimens were correctly identified as having no flaws (execpt for minor breakout) indicating at least a 95% confidence that a least 89 percent of the flaws would be found (see Appendix I for calculations).

MATERIAL	THICKNESS, IN.	BLADE TYPE(1)	SPEED, sfm	FEED, ipm	COOLANT(3)	FLAWS FOUND BEFORE MOISTURE CONDITIONING			FLAWS FOUND AFTER MOISTURE CONDITIONING			
						VISUAL	TRACER	PENETRANT	VISUAL	TRACER	PENETRANT	MINOR
GR/EP + B/EP	0.500	DIAMOND PLATED 60 GRIT	7154(2)	14	MIST	MINOR BREAKOUT	NONE	MINOR POROSITY	NO CHANGE	NONE	NO CHANGE	NONE
GR/EP	0.310		7154(2)	44	MIST	MINOR BREAKOUT	NONE	NONE	NO CHANGE	NONE	NONE	NONE
GR/EP	0.310		7154	102	MIST	MINOR PULLOUT	NONE	MINOR POROSITY	NO CHANGE	NONE	NO CHANGE	NONE
B/EP	0.125		7154	102	MIST	POROSITY	NONE	PORSITY	NO CHANGE	NONE	NO CHANGE	NONE
FG/EP	0.125		7154	24	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE
FG/EP	0.125		7154	69	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + B/EP	0.508		7154	14	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP	0.250		7154	32	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE

NOTES:

(1) SIDES GROUND

(2) BLADE EXTENDED 2.125 INCHES ABOVE WORK PIECE

(3) HANGSTERFERS – HE2 (20:1) WATER MIX

2199-187B

Figure 7-10 Moisture Conditioning Tests of Stationary Radially (Sawed Specimens)

MATERIAL	THICKNESS, IN.	BLADE TYPE(1)	SPEED, sfm	FEED, ipm	COOLANT(2)	FLAWS FOUND BEFORE MOISTURE CONDITIONING			FLAWS FOUND AFTER MOISTURE CONDITIONING			
						VISUAL	TRACER	PENETRANT	VISUAL	TRACER	PENETRANT	MICRO
GR/EP + B/EP	0.1185	DIAMOND PLATED 60 GRIT	2000	31	MIST	NONE	NONE	MINOR POROSITY	NONE	NONE	NO CHANGE	NONE
GR/EP + B/EP	0.485		2000	28	DRY	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + B/EP	0.485		4000	34	DRY	NONE	NONE	MINOR POROSITY	NONE	NONE	NO CHANGE	NONE
GR/EP + B/EP	0.091		4000	34	DRY	MINOR CRACKS	NONE	NONE	NO CHANGE	NONE	NONE	YES (NIL)
GR/EP + KEV/EP	0.280	TUNGSTEN CARBIDE COATED MED GRIT	4000	32	DRY	NONE	NONE	KEVLAR INTERFERED	NONE	NONE	NO CHANGE	NONE
GR/EP + B/EP	0.334		4000	13	DRY	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + KEV/EP	0.280		2000	21	DRY	NONE	NONE	KEVLAR INTERFERED	NONE	NONE	NO CHANGE	NONE
KEV/EP	0.118	CARBON(1) STEEL 32T	5400	55	DRY	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + FG/EP	0.250	TUNGSTEN CARBIDE COATED; MED GRIT	2000	17	DRY	MINOR DELAMIN-ATION	NONE	MINOR DELAMIN-ATION	NO CHANGE	NONE	NO CHANGE	YES (0.010")

NOTES:

(1) PRECISION WAVE SET

(2) HAMSTERFERS – HE-2 (20:1 WATER MIX)

2199-188B

Figure 7-11 Moisture Conditioning Tests of Bandsawed Specimens

MATERIAL	THICKNESS, IN.	BLADE TYPE	SPEED, sfm	FEED, ipm	COOLANT(3)	NDT METHOD					
						RADIOGRAPHY TRACER		MICRO-SECTIONING		VISUAL	PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND
GR/EP + B/EP	0.450	DIAMOND PLATED 60 GRIT(1)	7154	14	DRY	NO	NONE	NO	NONE	MINOR BREAKOUT	MINOR POROSITY
GR/EP	0.310		7154	102	MIST	NO	NONE	NO	NONE	MINOR PULLOUT	MINOR POROSITY
GR/EP + B/EP	0.450		7154(2)	14	MIST	NO	NONE	NO	NONE	MINOR BREAKOUT	NO
GR/EP	0.310		7154	44	MIST	NO	NONE	NO	NONE	MINOR BREAKOUT	NO
GR/EP + B/EP	0.508		7154	14	MIST	NO	NONE	NO	NONE	NO	NO
GR/EP	0.310		7154(3)	44	MIST	NO	NONE	NO	NONE	MINOR BREAKOUT	NO
GR/EP	0.500		7154	32	MIST	NO	NONE	NO	NONE	MINOR PULLOUT	NO
GR/EP	0.500		7154	32	MIST	NO	NONE	NO	NONE	NO	NO
B/EP	0.136		7154	69	MIST	NO	NONE	NO	NONE	POROSITY	POROSITY
B/EP	0.136		7154	102	MIST	NO	NONE	NO	NONE	POROSITY	POROSITY
B/EP	0.136		7154	102	MIST	NO	NONE	NO	NONE	POROSITY	POROSITY
GR/EP	0.310	TUNGSTEN CARBIDE COATED MED GRIT	5790	20	MIST	NO	NONE	NO	NONE	BREAKOUT	NO
GR/EP	0.490	DIAMOND PLATED 60 GRIT(2)	7154	69	MIST	NO	NONE	NO	NONE	MINOR POROSITY	MINOR POROSITY
GR/EP	0.310		7154(3)	44	MIST	NO	NONE	NO	NONE	MINOR POROSITY	MINOR POROSITY
GR/EP	0.500		7154	25	MIST	NO	NONE	NO	NONE	NO	NO
GR/EP	0.310		7154(3)	57	MIST	NO	NONE	NO	NONE	MINOR PULLOUT	NO
FG/EP	0.147		7154	24	MIST	NO	NONE	NO	NONE	NO	NO
FG/EP	0.147		7154	69	MIST	NO	NONE	NO	NONE	NO	NO

NOTES:
(1) SIDES GROUND
(2) SIDES NOT GROUND
(3) BLADE EXTENDED 2.125 INCHES ABOVE MATERIAL
(4) HANGSTERFERS-HE-2 (20:1 WATER MIX)

2199-189B

Figure 7-12 Stationary Radial Saw Nondestructive Evaluation

7.2.3.2 Bandsaw - Bandsawing produced more flaws than radial sawing (Figure 7-13). Most of the flaws were delaminations. The bandsaw also produced a rougher surface finish. All specimens which had flaws detected by tracer radiography also had the same flaws verified by microsectioning. One specimen which initially showed penetrant and did not show tracer radiography indications was verified by subsequent microsectioning. The depth of the delamination flaw was 0.010 inch, indicating a possible limitation of 0.010 inch for tracer radiography or possible saturation of the crack with penetrant (in the initial phases of the program, dye penetrant was performed on the specimens before tracer-radiography). The graphite/epoxy plus Kevlar/epoxy presented some problems with the tracer radiography in that absorption of the tracer by the Kevlar was so high that it would have prevented the detection of any flaws under 0.035 inch deep. Twenty-three bandsawed specimens were manufactured; eleven of them were delaminated as a result of the cutting operation. Nine of the eleven flaws were detected by tracer radiography (or 21 out of 23 correct) which statistically indicates (using the binomial distribution formula) at least a 95 percent confidence that 75% of all cracks seen by microsectioning would be found. Visual examination showed one missed flaw for a probability of 81% at 95% confidence and penetrant also showed one missed flaw (or 22 of 23 correct) for a similar 95% confidence at an 81% probability.

7.2.3.3 Hand Radial Saw - Data from the hand radial sawed specimens are presented in Figure 7-14. Fourteen specimens were tested and three were found to be delaminated by microsectioning. All three specimens which were delaminated were manufactured with Kevlar, indicating a tendency for that material to delaminate during hand radial sawing. The Kevlar also interfered with tracer-radiography, penetrant and even visual flaw detection. Tracer-radiography detected two of the three flawed specimens for a total of 13 correct of 14 or at least a 95% confidence that at least 71% of specimens were evaluated correctly. Penetrant and visual methods also found the same number of flawed specimens, resulting in the same probability of success and confidence level.

		NDT METHOD					
		RADIOGRAPHY TRACER		MICROSECTIONING		VISUAL	PENETRANT
SPECIMEN NO.	MATERIAL	FLAW FOUND	DEPTH (IN.)	FLAW FOUND	DEPTH (IN.)	FLAW FOUND	FLAW FOUND*
GR-1	GR/EP	YES	0.075	YES	0.075	YES	YES
GR-3	GR/EP	YES	0.040	YES	0.055	YES	YES
GR-7	GR/EP	YES	0.060	YES	0.060	YES	YES
GR-9	GR/EP	YES	0.070	YES	0.070	YES	YES
GR-GL-3	GR/EP + FG/EP	YES	0.035	YES	0.035	YES	YES
GR-GL-4	GR/EP + FG/EP	YES	0.020	YES	0.020	YES	POSSIBLE
GR-GL-6*	GR/EP + FG/EP	NO	NONE	YES	0.010	MINOR DELAMINATION	YES
GR-GL-8	GR/EP + FG/EP	YES	0.020	YES	0.025	YES	YES
TP-12-1-2	GR/EP	NO	NONE	NO	NONE	NO	NO
TP-12-4	KEV/EP	NO	NONE	NO	NONE	NO	NO
TP9-N1B	GR/EP	YES	0.035	YES	0.035	NO	YES
TP9-N2B	B/EP	NO	NONE	NO	NONE	NO	NO
TP9-N2C	GR/EP + BO/EP	NO	NONE	YES	NEGLIGENT	YES	NO
TP9-N2F	GR/EP + BO/EP	NO	NONE	NO	NONE	NO	NO
TP9-N3B	GR/EP + BO/EP	NO	NONE	NO	NONE	NO	NO
TP9-01B	GR/EP + BO/EP	NO	NONE	NO	NONE	NO	MINOR POROSITY
TP8-1B	FG/EP	NO	NONE	NO	NONE	NO	NO
TP8-3D	GR/EP + KEV/EP	NO	INTERFERENCE	NO	NONE	NO	NO
TP8-3F	GR/EP + KEV/EP	NO	INTERFERENCE	NO	NONE	NO	NO
TP8-3B	GR/EP + KEV/EP	NO	INTERFERENCE	NO	NONE	NO	NO
TP8-4B	GR/EP + B/EP	NO	NONE	NO	NONE	NO	NO
TP8-5A	GR/EP + B/EP	NO	NONE	NO	NONE	NO	NO
TP12-5	KEV/EP	YES	0.250	YES	0.250	YES	YES

*POSSIBLE SATURATION WITH PENETRANT OIL

2199-190B

Figure 7-13 Bandsaw NDT Evaluation

MATERIAL	THICKNESS, IN.	BLADE TYPE	SPEED, fpm	FEED ipm	COOLANT	NDT METHOD					
						RADIOGRAPHY TRACER		MICROSECTIONING		VISUAL	PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND*
GR/EP	0.267	DIAMOND PLATED 60 GRIT	7496	5B	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + FG/EP	0.260		7496	65	DRY	NO	NONE	NO	NONE	NO	NO
B/EP	0.136		7496	B6	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.333		7496	43	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.333		7496	43	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP	0.067		7496	132	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.090		7496	118	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.064		7496	9B	DRY	YES	0.065	YES	0.065	DE-LAMINATION	YES
GR/EP + FG/EP	0.064		7496	167	DRY	YES	0.125	YES	0.100	DE-LAMINATION	YES
FG/EP	0.147		7496	101	DRY	NO	NONE	NO	NONE	NO	NO
B/EP	0.135		7496	94	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP	0.275		7496	46	DRY	NO	NONE	NO	NONE	NO	NO
KEV/EP	0.112	CARBIDE 12 TEETH ALT OP-POSED FACE ANGLE	7496	96	DRY	(2)		NO	NONE	(2)	(1)
GR/EP + KEV/EP	0.271		7496	29	DRY	(2)		YES	0.060	NO	NO

(1) PENETRANT ABSORBED BY ALL KEVLAR TEST OBSCURED
(2) SPECIMEN TOO BADLY FRAYED

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Figure 7-14 Hand Radial Saw NDT Evaluation

7.2.3.4 Water Jet Cut - Data from the water jet cut specimens are listed in Figures 7-15 and 7-16. The data for Figure 7-15 were obtained through the normal evaluation procedure previously described for this program. The samples listed in Figure 7-16. were evaluated using tracer-radiography only. The results of water jet cutting are difficult to evaluate because of the sporadic nature of the damage caused by the operation. For example, Figure 7-17 shows the depth of delamination as determined by tracer radiography for graphite/epoxy and fiberglass/epoxy specimen No. G2-1. Note the sporadic depth of the delamination. Figure 7-18 further exemplifies the delamination nature of water jet cut as shown in a tracer-radiograph of a graphite/epoxy panel 0.181 in. thick (specimen 3A). The delamination is outlined by a white crayon along most of the photograph. Fifteen water jet specimens were evaluated (Figure 7-15) and ten of them were found to be cracked or delaminated by micro-sectioning. Tracer radiography found all ten flawed specimens and also identified one other (Specimen F2-1) as flawed. Since verification of the tracer-radiography flaw was not confirmed by microsectioning, the assumption will be made that a false positive resulted, through it is possible the flaw was lost during the microsectioning. Consequently, tracer radiography diagnosed 14 of the 15 specimens properly for a success probability of 73% at a confidence of 95% penetrant identified all flawed specimens with no false positive data for a success probability of 87% at 95% confidence. Visual methods misidentified five specimens or 10 out of 15 successfully which statistically indicates a 95 percent confidence that at least 42% of the proper identification will be made for these specimens.

A review of Figure 7-16 shows that water jet pressure has a decided effect on the degree of delamination. Specimens with the highest pressure (60 kpsi) appeared to have the lowest delamination penetration.

7.2.3.5 Hand Routing - The hand-routed specimens (Figure 7-19) were examined and six of the twenty-five samples were found to be cracked. Tracer-radiography verified five of the six flaws, and located two additional flaws found on the surface of the specimen. The one flaw not detected by tracer-radiography was again a Kevlar material (specimen R4-2) which interfered with the NDE method. Since 20 of 21 specimens were correctly evaluated, this indicates a 95% confidence. It can be expected that at least 81% of all the specimens would be evaluated properly by tracer-radiography.

MATERIAL	THICKNESS, IN.	PRESSURE, KSF	STAND OFF, IN.	NOZZLE DIA, IN.	FEED, ipm	NDT METHOD					
						RADIOGRAPHY TRACER		MICRO-SECTIONING		VISUAL	PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND
GR/EP	0.062	55	3/16	0.008	60	YES	0.075	YES	0.021	CRACK	YES
GR/EP	0.134	60	3/16	0.010	30	YES	0.375	YES	0.390	DELAMINATION	YES
GR/EP	0.275	60	1/8	0.014	6.6	YES	0.110	YES	0.300	CRACK	YES
B/EP	0.058	60	3/16	0.012	120	YES	0.250	YES	0.300	NO	YES
B/EP	0.136	60	1/8	0.010	120	YES	0.285	YES	0.290	DELAMINATION	YES
KEV/EP	0.062	55	1/8	0.006	120	YES	THRU CRACK	YES	THRU CRACK	NO	YES
KEP/EP	0.123	55	1/8	0.010	6.6	NO	NONE	NO	NONE	NO	NO
FG/EP	0.143	60	3/16	0.010	6.0	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.095	60	1/8	0.012	14	YES	0.05	YES	0.100	NO	YES
GR/EP + B/EP	0.154	60	1/8	0.012	4	YES	0.090	YES	0.200	MINOR CRACKS	YES
GR/EP + KEV/EP	0.063	60	1/8	0.010	16	NO	NONE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.267	60	1/8	0.014	5	YES(1)	0.100	NO	NONE	NO	NO
GR/EPT + FG/EP	0.067	55	1/8	0.012	9	YES	0.075	YES	0.075	NO	YES
GR/EP + FG/EP	0.253	60	1/16	0.012	9	YES	0.125	YES	0.290	NO	YES
GR/EP + B/EP	0.321	60	1/8	0.014	9	NO	NONE	NO	NONE	NO	NO

(1) CRACK MAY HAVE BEEN CUT OUT DURING SECTIONING

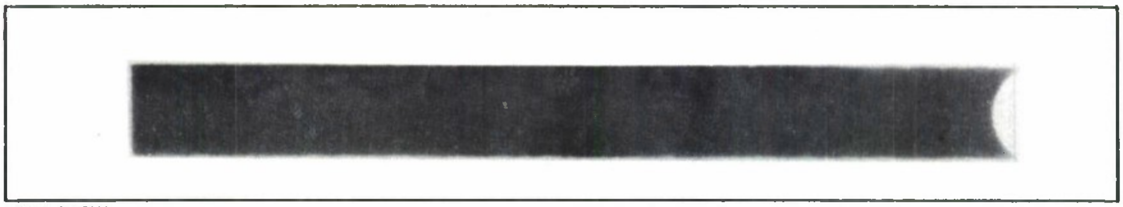
2199-192B

Figure 7-15 Water Jet NDT Evaluation (Flow Industries Inc.)

MATERIAL	THICKNESS IN.	COMPANY	PRESSURE, kpsi	STAND OFF IN.	NOZZLE DIA IN.	NDT METHOD			
						FEED RATE ipm	RADIOGRAPHY TRACER		COMMENTS
							FLAW FOUND	DEPTH, IN.	
GR/EP	0.090	ITTRI	81	0.5	0.24	270	YES	0.025 – 0.445	SPORADIC DELAMINATION
GR/EP	0.181	ITTRI	100	0.5	0.40	270	YES	0.300 – 0.110	CONTINUOUS DELAMINATION
GR/EP	0.131	MCCARTNEY	40 TO 50	0.5	0.010	72	YES	0.080 – 0.110	
GR/EP	0.134	FLOW IND	60	3/16	0.010	45	YES	0.130 – 0.300	SPORADIC
GR/EP	0.134		60	3/16	0.010	30	YES	0.025	CONTINUOUS GOOD SPECIMEN
GR/EP	0.134		60	3/16	0.008	30	YES	0.075 – 0.220	SPORADIC
GR/EP	0.134		55	3/16	0.012	30	YES	0.175	SPORADIC
GR/EP	0.063		50	3/16	0.012	30	YES	0.080 – 0.300	
GR/EP	0.134		55	3/16	0.010	30	YES	0.120 – 0.350	
GR/EP	0.134		60	3/16	0.010	60	YES	0.080 – 0.220	
GR/EP	0.134		40	3/16	0.012	30	YES	0.150 – 0.400	
GR/EP	0.063		55	3/16	0.005	120	YES	0.165	
GR/EP	0.063		60	3/16	0.008	120	YES	0.060	
GR/EP	0.063		55	3/16	0.008	120	YES	0.095	
GR/EP	0.063		35	3/16	0.008	120	YES	0.230	
GR/EP	0.063		55	3/16	0.008	30	YES	0.115	
GR/EP	0.063		60	3/16	0.012	30	YES	0.050	
GR/EP	0.063		55	3/16	0.008	45	YES	0.100	
GR/EP	0.063		50	3/16	0.012	120	YES	0.130	
GR/EP	0.063		60	3/16	0.010	120	YES	0.030 – 0.080	
GR/EP	0.063		55	3/16	0.008	60	YES	0.120	
GR/EP	0.134		60	3/16	0.012	60	YES	0.025 – 0.050	

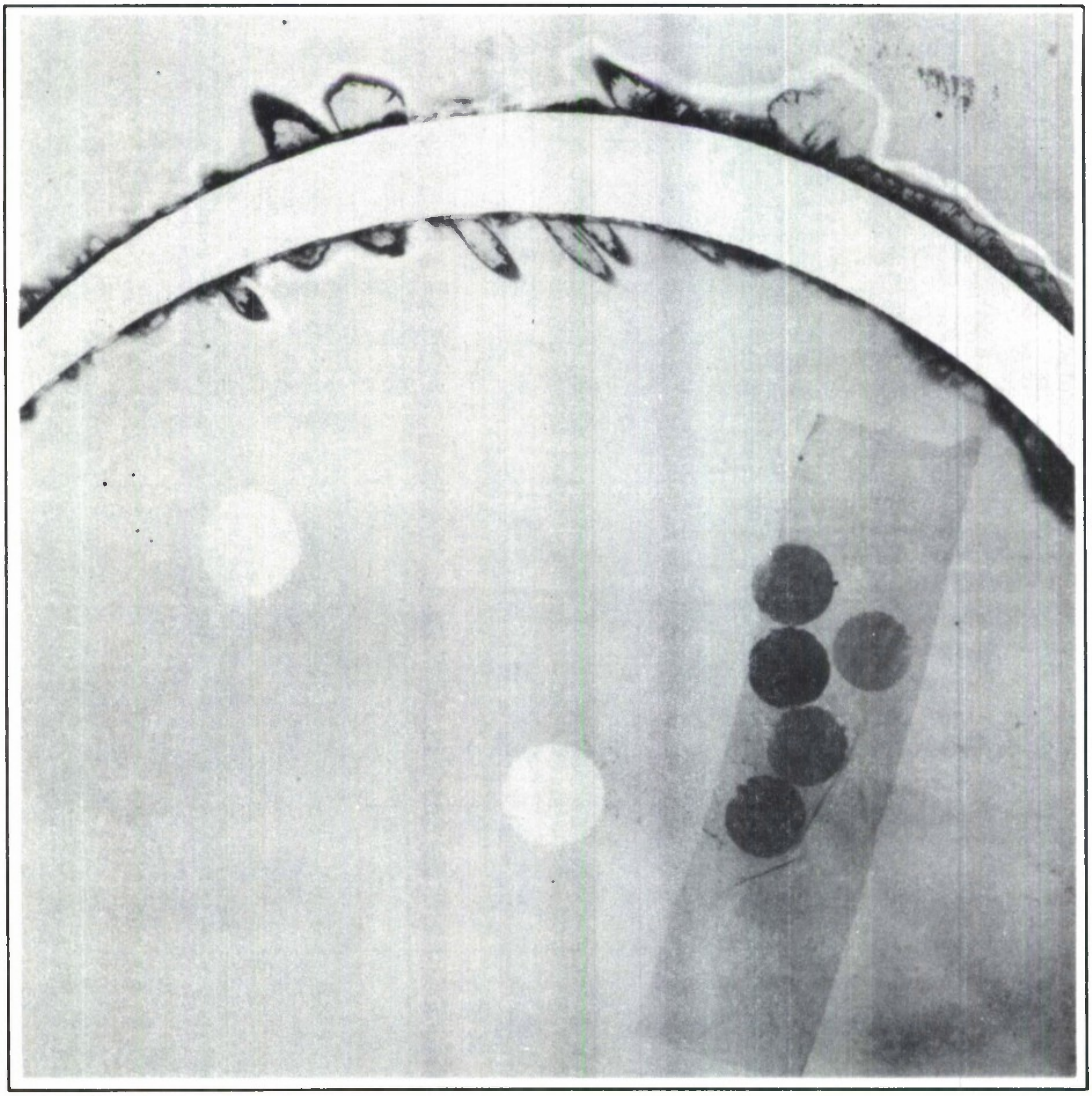
2199-193B

Figure 7-16 Water Jet Evaluation



2566-068W

Figure 7-17 Delamination in Graphite/Epoxy Plus Fiberglass/Epoxy Specimen



2566-069W

Figure 7-18 Tracer-Radiographic Examination of Water-Jet Cut Fiberglass/Epoxy Panel

MATERIAL	THICKNESS, IN.	SPEED, sfm	FEED, ipm	CUTTER TYPE	COOLANT(4)	NDT METHOD: RADIOGRAPHY TRACER		NDT METHOD: MICRO-SECTIONING		NDT METHOD: VISUAL	NDT METHOD: PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND
GR/EP	0.132	851	46	CARBIDE DIAMOND CUT	MIST	NO	NONE	NO	NONE	NO	YES
GR/EP	0.132	851	46			NO	NONE	NO	NONE	NO	YES
GR/EP	0.272	851	30			YES	0.030	NO(2)	NONE	YES	YES
GR/EP	0.272	851	30			YES	0.020	NO(2)	NONE	YES	NO
GR/EP	0.132	851	22			NO	NONE	NO	NONE	NO	YES
GR Q	0.132	851	22			NO	NONE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.287	851	14			(1)		NO	NONE	NO	NO
GR/EP + KEV/EP	0.287	851	14			(1)		YES	0.100	NO	NO
FG/EP	0.148	851	27			NO	NONE	NO	NONE	NO	YES
FG/EP	0.148	851	27			NO	NONE	NO	NONE	NO	YES
GR/EP + FG/EP	0.266	851	16			NO	NONE	NO	NONE	NO	YES
GR/EP + FG/EP	0.266	851	16			YES	0.020	NO	NONE	NO	YES
GR/EP	0.068	851	83			YES	0.050	YES	0.025	DE-LAMINATION	YES
GR/EP	0.068	851	83			YES	0.065	NO(3)	NONE	NO	NO
GR/EP + KEV/EP	0.075	851	60			(1)		NO	NONE	(1)	(1)
GR/EP + KEV/EP	0.075	851	60			(1)		NO	NONE	(1)	(1)
GR/EP + FG/EP	0.065	851	85			YES	0.020	YES	0.035	NO	YES
GR/EP + FG/EP	0.065	851	85			NO	NONE	NO	NONE	NO	NO
GR/EP	0.132	1435	13			YES	0.030	YES	0.050	NO	YES
GR/EP	0.132	1435	13			NO	NONE	NO	NONE	NO	YES MINOR
FG/EP	0.148	1435	18			YES	0.050	YES	0.100	NO	YES
FG/EP	0.148	1435	18			NO	NONE	NO	NONE	NO	NO
GR/EP	0.068	1435	82			NO	NONE	NO	NONE	NO	NO
GR/EP	0.066	1435	82			NO	NONE	NO	NONE	NO	YES
GR/EP	0.272	1435	82			YES	0.050	YES	0.055	DE-LAMINATION	YES DELAM

(1) INTERFERENCE BY KEVLAR
(2) SURFACE FLAW
(3) FLAW CUT BY CUT OFF WHEEL
(4) HANGSTERFERS-HE-2 (20:1 WATER MIX)

2199-196B

Figure 7-19 Hand Routing NDT Evaluation

Four specimens were incorrectly evaluated by visual means. Nineteen of twenty-three were successfully detected giving a 64% probability and a 95% confidence for flaw detection. Six specimens (8 out of 23) were incorrectly identified as being flawed (flase positives) by penetrant giving rise to a low probability of 45% with a 95% confidence. Most of the problems attributed to some specimens not being evaluated stems from the very poor surface conditions caused by the hand routing operation. Many specimens, especially Kevlar, were badly frayed or had breakout, causing difficulty in evaluating the specimens. The graphite/epoxy specimens were relatively good.

7.2.3.6 Machine Routing - The evaluation of the routed specimens is summarized in Figure 7-20. Seventeen specimens were examined from three routers: Onsrud (OR specimens), Marwin (MR Specimens) and Roto-Reciprocating (RR specimens). The Onsrud routine operation caused the most damage to the specimens by cracking, delaminating and fraying or shredding the edge. Transverse cracks, the thickness of the graphite laminate in the composite, were found randomly along the entire length of two of the Onsrud specimens. Figure 7-21 shows these microcracks, approximately 0.010-inch long, in specimen OR15-1, which were found in the graphite material.

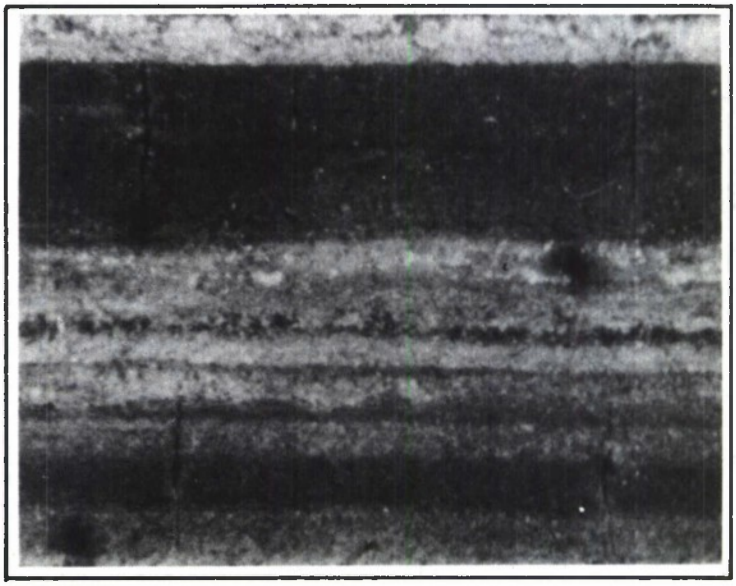
Six flawed routing specimens were detected from the seventeen examined. Two of the specimens had to be substantiated by means other than microsectioning since the cracks were too small. Tracer-radiography detected five of the flaws, or 16 of 17 specimens evaluated correctly for a 75% probability and 95% confidence of accurate detection. Visual examination determined the same number flaws existed for the same statistical inference, and penetrant evaluation incorrectly identify three false positives and missed three flaws for a total of 10 out of 16 successful tests of a probability of 37% with a 95% confidence.

MATERIAL	THICKNESS, IN.	MACHINE TYPE	SPEED, sfm	FEED ipm	STROKES PER MIN	CUTTER TYPE	COOLANT(3)	NDT METHOD					
								RADIOGRAPHY TRACER		MICRO-SECTIONING		VISUAL	PENETRANT
								FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND
GR/EP + KEV/EP	0.064	ONSRUD	1315	44	–	CARBIDE OPPOSED HELIX	DRY	YES	0.065	YES	0.065	DE-LAMINATION	(1)
GR/EP + KEV/EP	0.263	ONSRUD	1315	B	–		DRY	YES	0.020	NO(2)	NONE	TRANSVERSE CRACKS/ DELAM	YES
GR/EP + KEV/EP	0.263	ONSRUD	1315	B	–		DRY	YES	0.035	NO(2)	NONE	TRANSVERSE CRACKS/ DELAM	YES
KEV/EP	0.102	ONSRUD	1315	59	–		DRY	YES	0.050	YES	0.090	YES	NO
KEV/EP	0.102	ONSRUD	1315	59	–		DRY	YES	0.070	YES	0.075	YES	NO
GR/EP	0.0B6	ONSRUD	723	29	–	CARBIDE DIAMOND CUT	MIST	NO	NONE	NO	NONE	NO	NO
GR/EP	0.2B7	MARWIN	723	10	–		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + FG/EP	0.063	MARWIN	723	24	–		MIST	NO	NONE	NO	NONE	NO	YES
GR/EP + FG/EP	0.263	MARWIN	723	12	–		MIST	NO	NONE	NO	NONE	NO	NO
FG/EP	0.144	MARWIN	723	22	–		MIST	NO	NONE	NO	NONE	NO	YES
B/EP	0.136	ROTO-RECIPRO	723	4	60	DIAMOND PLATED 40-50 GRIT	MIST	NO	NONE	NO	NONE	NO	NO
B/EP	0.136	ROTO-RECIPRO	B51	4	200		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.090	ROTO-RECIPRO	B51	5	60		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + 8/EP	0.090	ROTO-RECIPRO	B51	5	200		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.346	ROTO-RECIPRO	851	5	60		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.346	ROTO-RECIPRO	851	5	60		MIST	NO	NONE	YES	0.030	NO	NO
GR/EP + B/EP	0.500	ROTO-RECIPRO	B51	3	200		MIST	NO	NONE	NO	NONE	NO	NONE

NOTES:
(1) INTERFERENCE FROM KEVLAR
(2) CRACKS TO SMALL TO MICROSECTION
(3) HANGSTERFERS-HE-2 (20:1 WATER MIX)

2199-197B

Figure 7-20 Machine Routing NDT Evaluation



2566-071W

Figure 7-21 Cracks Found in the Transverse Direction of Graphite/Epoxy Laminate (60X Mag)

7.2.3.7 Trimming - Figure 7-22 shows the results of NDE of the trimmed specimens. Seven specimens were evaluated and four were found to be cracked. One specimen from the Onsrud routing again showed transverse cracks. The Kevlar specimens again interfered with visual tracer and penetrant tests giving rise to false positive or samples not evaluated.

7.2.3.8 Beveling - Figure 7-23 shows the results of the beveling specimens. The operation does not lend itself well to tracer-radiography because of the beveled edge. Penetrant appears to be the best approach for this operation.

7.2.3.9 Drilling Operations - Drilling operations produce certain consistent flaws which are easily detected. The most prevalent condition is breakout of the bottom surface as the drill exits from the composite material. Figure 7-24 shows typical breakout from several holes in a graphite/epoxy panel. This condition can be seen visually and detected by tracer-fluoroscopy/radiography as required. Other problems experienced with drilling were entrance and exit delaminations. Most often, the surface finish of the hole interfered with penetrant evaluation, since the rough surface texture trapped the penetrant liquid and subsequently gave false positive indications on evaluation.

Microsectioning revealed that tracer-radiography accurately detected the depth and scope of all delaminations and cracks. Consequently, that method was used as a baseline for the drilling damage evaluation. The material which gave the most problems with regard to evaluation was Kevlar/epoxy or hybrid Kevlar-graphite/epoxy panels. Kevlar has a strong tendency to fray or shred during machining operations and usually makes evaluation by any method that relies on liquid penetration invalid. As a result, certain Kevlar panels (Tests 47-61, A and B) could not be evaluated with the tracer-radiography or penetrant method. Visual evaluation was also difficult for the same reasons.

As described above, the most common problem associated with drilling is breakout, followed by delamination around the hole area. Figure 7-25 shows the results of the evaluation of holes drilled in graphite/epoxy panels. Tracer-radiography gave the best evaluation of the damaged areas. Because the dye-penetrant method generally resulted in many false positive indications, the reliability of this method for accurate flaw detection is questionable. Visual examination was necessary to assist in evaluating the overall quality of the holes.

MATERIAL	THICKNESS, IN.	MACHINE TYPE	SPEED, sfm	FEED ipm	STROKES PER MIN	CUTTER TYPE	COOLANT	NDT METHOD					
								RADIOGRAPHY TRACER		MICRO-SECTIONING		VISUAL	PENETRANT
								FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND
GR/EP + KEV/EP	0.263	ONSRUD	1315	35	–	CARBIDE OPPOSED HELIX	DRY	YES	0.060	YES	0.100	TRANSVERSE	YES
GR/EP + KEV/EP	0.064	ONSRUD	1315	76	–		DRY	YES	0.030	NO	NO	NO	(1)
KEV/EP	0.102	ONSRUD	1315	64	–		DRY	YES	0.035	NO	NO	NO	
GR/EP + B/EP	0.090	ROTO-RECIPRO	851	20	200	DIAMOND PLATED 40–50 GRIT	MIST	YES	0.090	YES	0.100	YES	YES
B/EP	0.136		851	20	200		MIST	NO	NONE	NO	NONE	YES	YES
GR/EP + B/EP	0.346		851	9	200		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.500		851	9	200		MIST	NO	NONE	NO	NONE	NO	NO

NOTES:
(1) INTERFERENCE FROM KEVLAR
(2) HANGSTERFERS-HE-2 (20:1 WATER MIX)

Figure 7-22 Machine Trimming NDT Evaluation

MATERIAL	THICKNESS, IN.	SPEED, sfm	FEED, ipm	CUTTER TYPE	COOLANT(1)	NDT METHOD					
						RADIOGRAPHY TRACER		MICRO-SECTIONING		VISUAL	PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND
GR/EP	0.272	851	47	CARBIDE DIAMOND CUT	MIST	NO	NONE	YES	0.065	NO	YES
GR/EP + FG/EP	0.245	851	58		MIST	NO	NONE	NO	NONE	NO	NO
FG/EP	0.148	851	57		MIST	NO	NONE	NO	NONE	NO	NO

NOTE:
(1) HANGSTERFERS-HE-2 (20:1 WATER MIX)

2566-179W

Figure 7-23 Manual Beveling NDT Evaluation

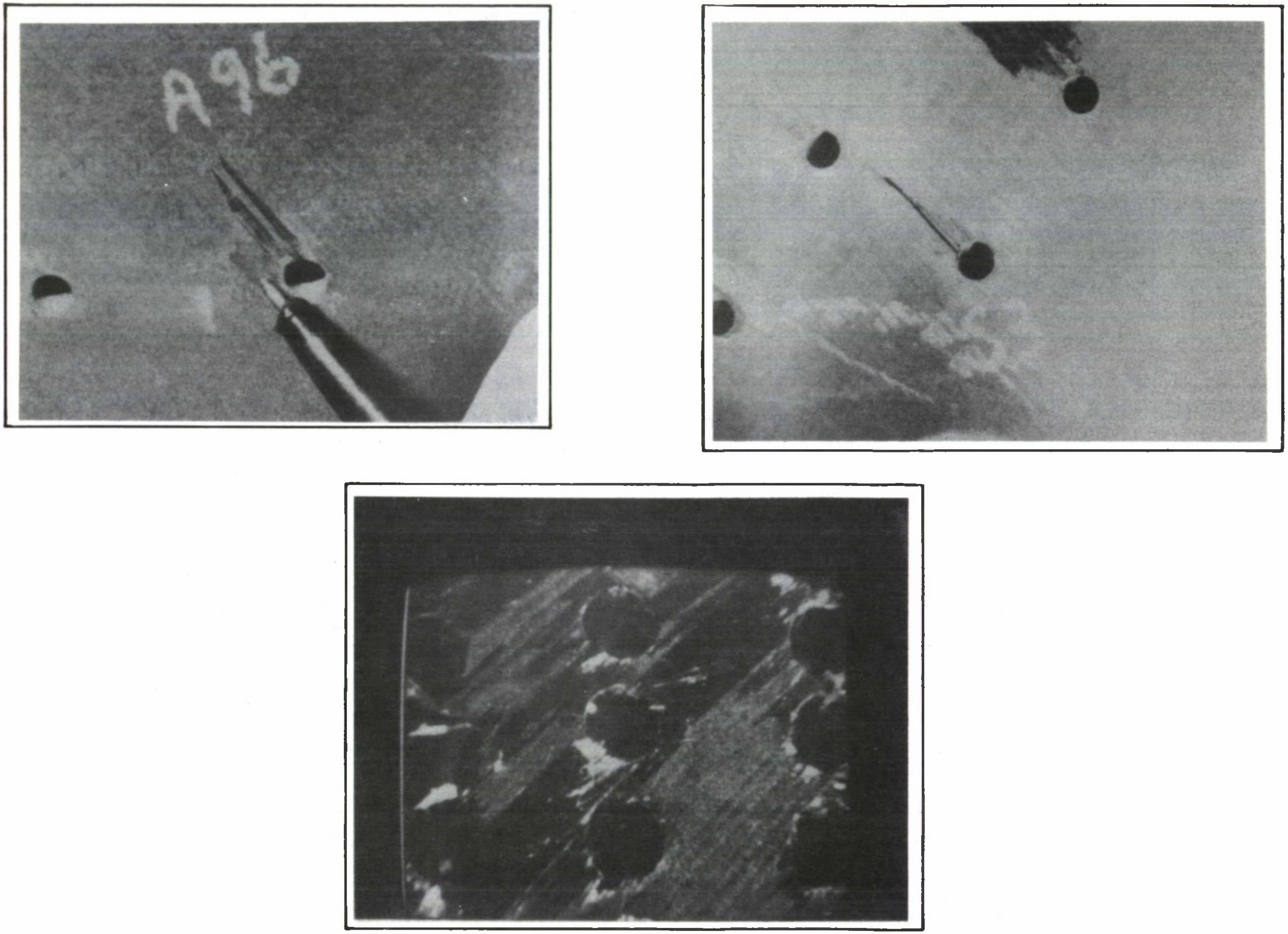


Figure 7-24 Holes in Graphite/Epoxy Panels Showing Breakout Condition as a Result of Drilling

2199-201B

MATERIAL	THICKNESS IN.	DRILL TYPE	SPEED rpm	FEED ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY	0.300	1/8 DIA ROTA-KOTE	6000	0.001	0.020" – 0.085" DELAMINATION ON ALL HOLES	SMALL HOLES DIFFICULT TO TEST. MANY INDICATION DRILL MARKS GIVE FALSE POSITIVES	ALL HOLES FAIRLY SMOOTH; ALL HAVE BREAKOUTS PROGRESSIVELY WORSTENING TO LAST HOLE
GRAPHITE/ EPOXY	0.300	3/16 DIA ROTA-KOTE CARBIDE	6000	0.001	0 – 0.200" DELAMINATION ON ALL HOLES WORSE TOWARD LAST		FIRST HOLES FAIRLY SMOOTH BUT BECOME ROUGHER. ALL HOLES HAVE BREAKOUT WITH CONDITION WORSTENING AT LAST 50 HOLES
GRAPHITE/ EPOXY	0.275	15/16 DIA DIAMOND-TIPPED (80-100 GRIT)	6000	0.001	ALL HOLE DELAM-INATED 0.100" – 0.125"		HOLES FAIRLY SMOOTH, LITTLE BREAKOUT
GRAPHITE/ EPOXY	0.275	1/4 DIA DIAMOND-TIPPED (220 GRIT)	6000	0.001	ALL HOLES DELAM-INATED 0.055" – 0.125"		HOLES CLEAN; MINOR BREAKOUT ON LASY PLYS
GRAPHITE/ EPOXY	0.275	1/4 DIA DIAMOND-TIPPED (100 – 120 GRIT)	6000	0.001	ALL HOLES DELAMINATED 0.50" – 0.130"	BREAKOUT AND DELAMINATION CAN BE SEEN AT BOTTOM OF HOLE. MANY FALSE POSITIVES	MINOR FIBER PULLOUT IN LAST THREE HOLES; MINOR BREAKOUT
GRAPHITE/ EPOXY	0.275	1/4 DIA CARBIDE-TIPPED	6000	0.001	ALL HOLES DELAMINATED 0.010" 0.075" NO RELATIONSHIP TO NUMBER OF HOLES DRILLED		FIBER PULLOUT IN ALL HOLES; BREAKOUT INCREASES AS NO. OF HOLES INCREASE, SOME DELAMINATION ON ENTRANCE SIDE.
GRAPHITE/ EPOXY	0.300	1/4 DIA MICROGRAINED CARBIDE	6000	0.001	ALL HOLES DELAMINATED 0 – 0.125" DELAMINATION WORSTENING FROM HOLE 1 to 60		FIBER PULLOUT BECOMES PROGRESSIVELY WORSE WITH INCREASED HOLE NUMBER NO SIGNIFICANT BREAKOUT FOR FIRST 20 HOLES. THEN BREAKOUT INCREASES TO LAST HOLE
GRAPHITE/ EPOXY	0.275	1/4 DIA FISH TAIL POINT, CARBIDE-TIPPED	6000	0.001	ALL HOLES DELAMINATED 0.055" – 0.130"		FIBER PULLOUT IN ALL HOLES, MINOR BREAKOUT FROM ALL HOLES
GRAPHITE/ EPOXY	0.300	1/8 DIA ROTA-KOTE HSS	6000	0.001	DELAMINATION AND BREAKOUT ON ALL HOLES TO 0.125" MAX.	MANY INDICATORS HOLES SMALL TO TEST ACCURATELY	SOME FIBER PULLOUT; BAD BREAKOUT ON ALL HOLES
GRAPHITE/ EPOXY	0.275	0.190 DIA ROTA-KOTE HSS	6000	0.001	ALL HOLES DE-LAMINATED 0.110" – 0.140"	SOME FALSE INDICATIONS	HOLES FAIRLY SMOOTH SOME FIBER PULLOUT BREAKOUT ON ALL HOLES;

2199-202B(1)

Figure 7-25 Summary of Non-Destructive Evaluation of Drilled Holes (Sheet 1 of 2)

MATERIAL	THICKNESS, IN.	DRILL TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY	0.270	0.250 DIA TWIST HSS	3000	0.003	DELAMINATION OF HOLE 1 OF 0.120" PROGRESSING TO 0.150" AT LAST HOLE	MATERIAL IN HOLE HOLDS PENETRANT, FALSE INDICATIONS	HOLE SMOOTH AT FIRST PROGRESSIVELY GETTING ROUGHER TO HOLE 14. BAD BREAKOUT ON ALL HOLES.
GRAPHITE/ EPOXY	0.270	0.250 DIA TWIST HSS	6000	0.003	DELAMINATION IN ALL HOLES 0.120" – 0.150"		ALL HOLES FAIRLY SMOOTH OF SOME QUALITY THROUGH ALL SIX SOME FIBER PULLOUT, BAD BREAKOUT ON ALL HOLES
GRAPHITE/ EPOXY	0.270	0.250 DIA CARBIDE TIPPED	6000	0.001	ALL HOLES DELAMINATED 0.120" – 0.150"		HOLE QUALITY ESSENTIALLY THE SAME THROUGH OUT ALL 60 HOLES, BREAKOUT ON ALL HOLES; SOME GOUGING BY DRILL.
GRAPHITE/ EPOXY	00.270	0.190 DIA CARBIDE DRILL/C'SINK Z114104 0.2055 DIA	6000	0.001	HOLES DELAMINATED 0.080"		HOLE QUALITY SIMILAR FOR ALL 140 HOLES. ALL HOLES DELAMINATED WITH BREAKOUT.
GRAPHITE/ EPOXY	0.270	MEGADIAMOND TIPPED	2500 4500	0.001	DELAMINATION AT HOLE 1 of 0.120" PROGRESSING TO 0.150" AT HOLE #60		HOLE QUALITY THE SAME FOR ALL 60 HOLES. SOME FIBER PULLOUT, ALL HOLES HAVE BREAKOUT
GRAPHITE/ EPOXY	0.275	0.250 DIA TWIST, CARBIDE TIPPED	21,600	0.001	DELAMINATION AT HOLE # 1 OF 0.005" PROGRESSING TO 0.125" AT HOLE # 120	PENETRANT GIVES MANY FALSE POSITIVES	FAIR SURFACE FINISH IN ALL 120 HOLES. ALL HOLES HAVE BREAKOUT
GRAPHITE/ EPOXY	0.275	0.190 DIA CARBIDE Z114104	21,000	0.001	DELAMINATION AT HOLE # 1 OF 0.050 PROGRESSING TO 0.130" AT LAST HOLE # 250		FAIR SURFACE FINISH IN ALL 250 HOLES. ALL HOLES HAVE BREAKOUT

2199-202B(2)

Figure 7-25 Summary of Non-Destructive Evaluation of Drilled Holes (Sheet 2 of 2)

Figures 7-26, 7-27, and 7-28 show typical delaminations and breakouts in graphite/epoxy panels. Some of the holes in Figure 7-26 (Test 16) were not impregnated to contrast the effect of the tracer.

Figure 7-29 summarizes the results of nondestructive evaluation (NDE) of ultrasonically drilled panels backed up with masonite. The results of this operation were good with little delamination of the holes. Figure 7-30 shows the tracer-radiograph of Test C on the ultrasonically drilled holes in graphite/epoxy plus boron/epoxy panels. The NDE results of drilled Kevlar/epoxy panels are summarized in Figure 7-31. Most of the penetrant tests were invalidated by absorption of the penetrant by the Kevlar. Although some interference was experienced with the tracer-radiograph method, sufficient information was obtained to define the flawed areas. Figure 7-32 shows the holes in the graphite/epoxy plus Kevlar/epoxy panel which delaminated (Test 13) as a result of drilling.

7.2.3.10 Countersinking. Except for the Kevlar/epoxy panels, NDE of countersunk holes showed that good quality countersinks were obtained. The use of tracer-radiography is effective only when attempting to find delaminations that originate from the upper surface of the countersunk areas. This is due to the nature of the countersink configuration which hinders tracer-radiography because the slope of the countersink masks the area below it. Since all flaws found in the countersunk holes were surface delaminations, tracer-radiography worked well. Figure 7-33 shows the NDE results of countersink panels. Although most countersinks were clean, some interference was encountered with the graphite/epoxy plus Kevlar/epoxy panel.

7.2.3.11 Counterboring. NDE showed the counterboring gave good results. Kevlar interfered with the penetrant and tracer-radiography tests as expected. The counterbored holes had little delamination at the hole entrance. Most holes were clean and showed few penetrant indications. Figure 7-34 shows the NDE results of counterbored panels. Figure 7-35 shows a tracer-radiograph of the fiberglass/epoxy counterbored test panel. The dark area around the outside of the counterbored holes delineates the delaminated areas.

7.2.4 Summary

The assignment of flaw size constraints to composite designs must take into consideration the difficulty and cost of locating and detecting these flaws. For flaws such as cracks and delaminations more than 0.010 inch from the edge of the material, tracer-radiography is the best method for detection and sizing. Penetrant inspection offers an effective back up for tracer-radiography, if smaller surface flaws such as

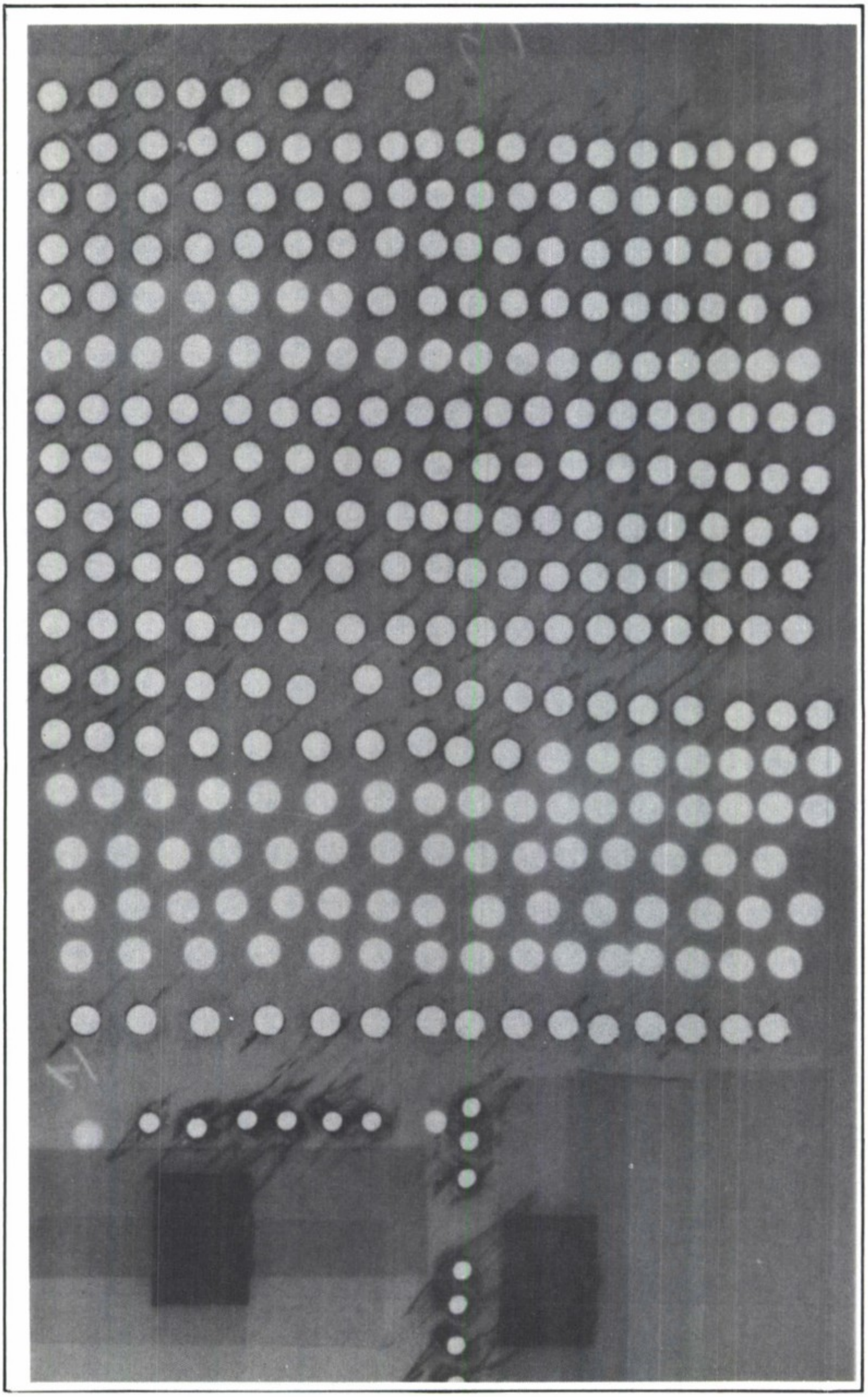


Figure 7-26 Typical Delamination and Hole Breakout in Drilled 0.200-Inch-Thick Graphite/Epoxy Panel

2199-203B

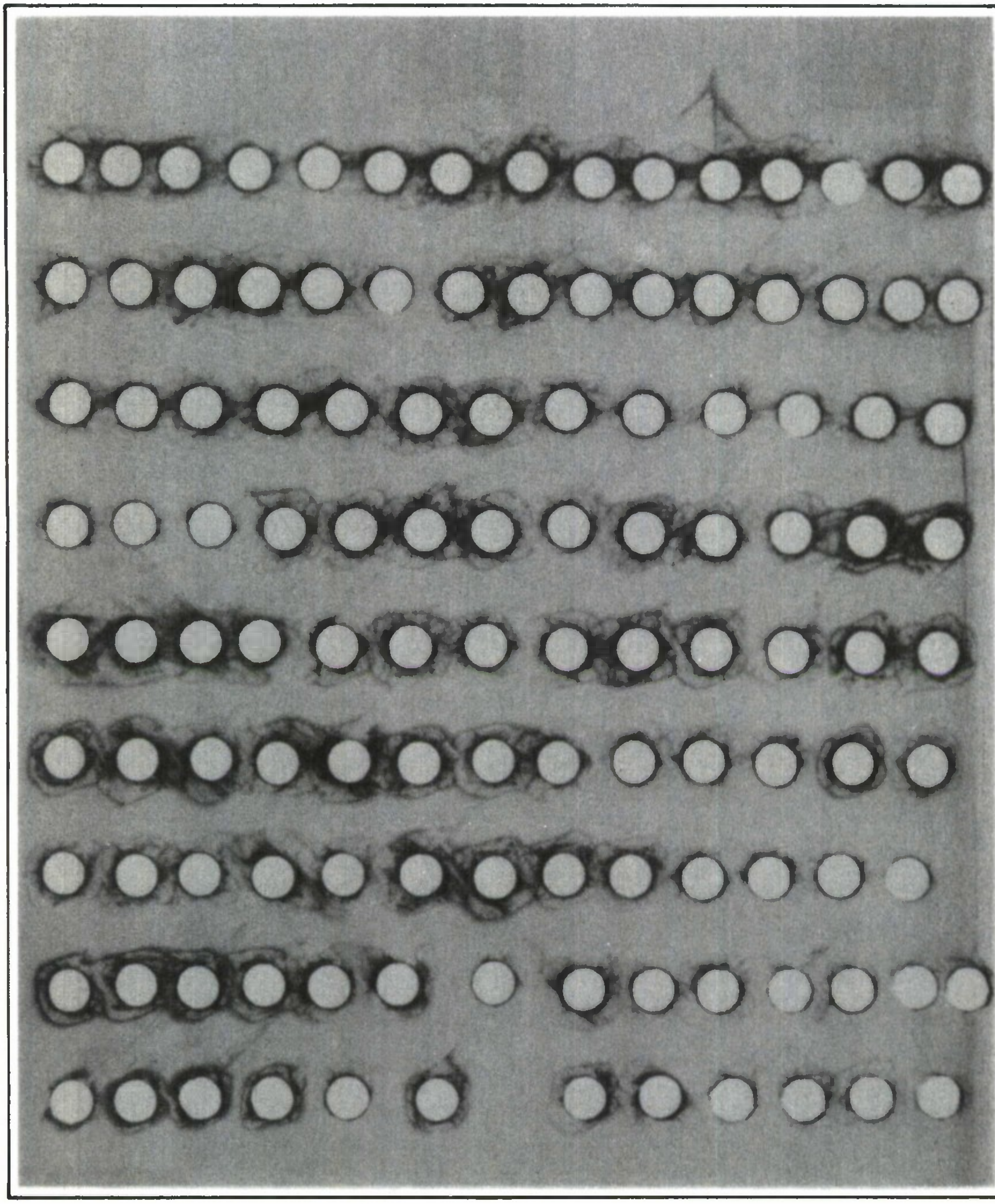


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Figure 7-27 Typical Delamination and Hole Breakout in Drilled 0.275-Inch-Thick Graphite/Epoxy Panel

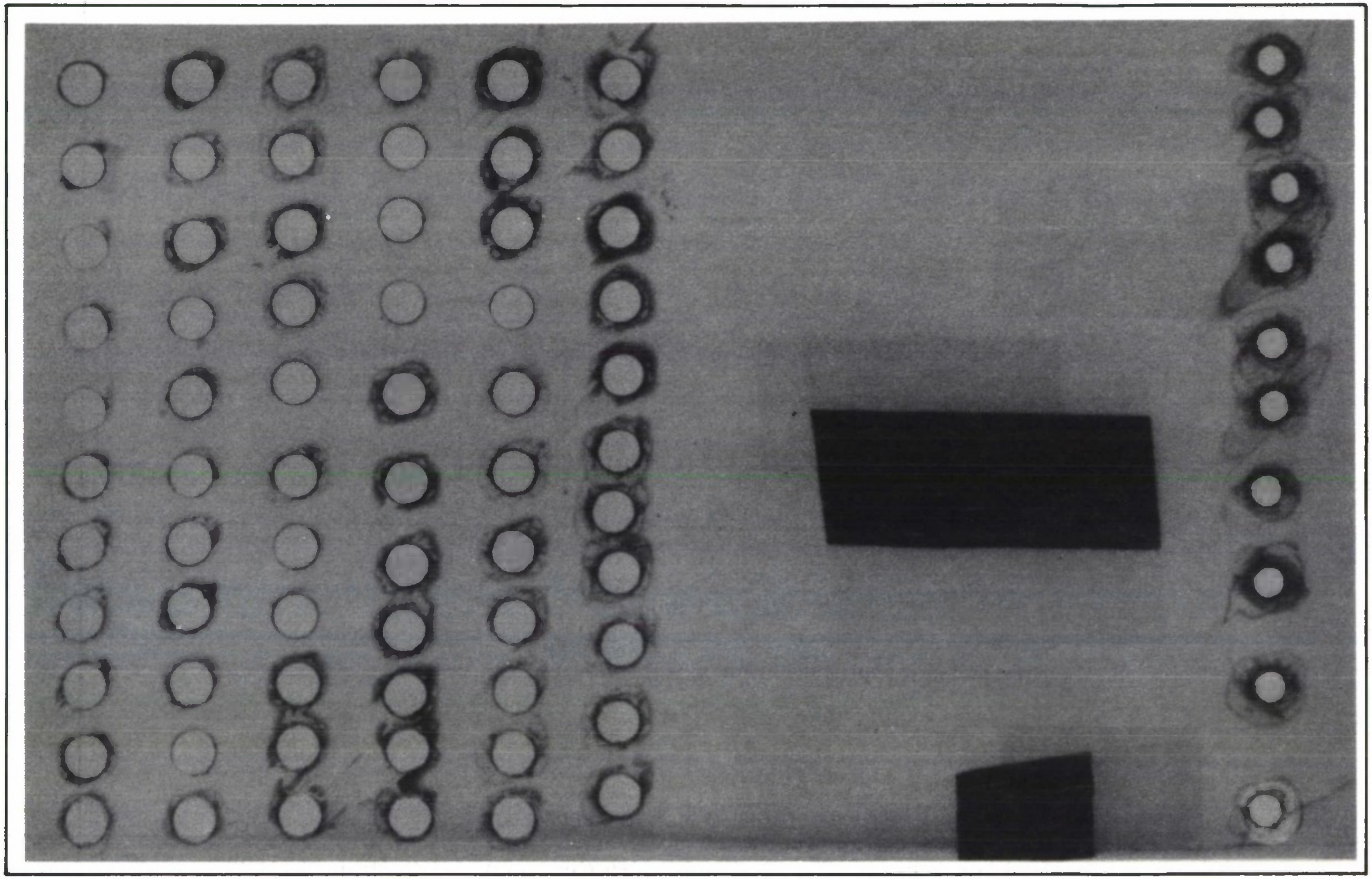

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Figure 7-28 Typical Delamination and Hole Breakout In Drilled 0.275-Inch-Thick Graphite/Epoxy Panel

MATERIAL	THICKNESS IN.	DRILL TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY + BORON/ EPOXY	0.223	3/16 DIA QUACKEN-BUSH ULTRASONIC	3000	0.005	27 OF 75 HOLES DELAMINATED 0.055" – 0.070" OTHER HOLES ACCEPTABLE	SOME DELAMIN-ATIONS PICK UP IN HOLE SOME FALSE POSITIVES	HOLES BACKED BY MASONITE; GETTING PROGRESSIVELY WORSE TOWARD HOLE # 75. SOME BREAKOUT; SURFACE RELATIVELY SMOOTH

2199-206B

Figure 7-29 Summary of Non-Destructive Evaluation of Ultrasonically Drilled Holes

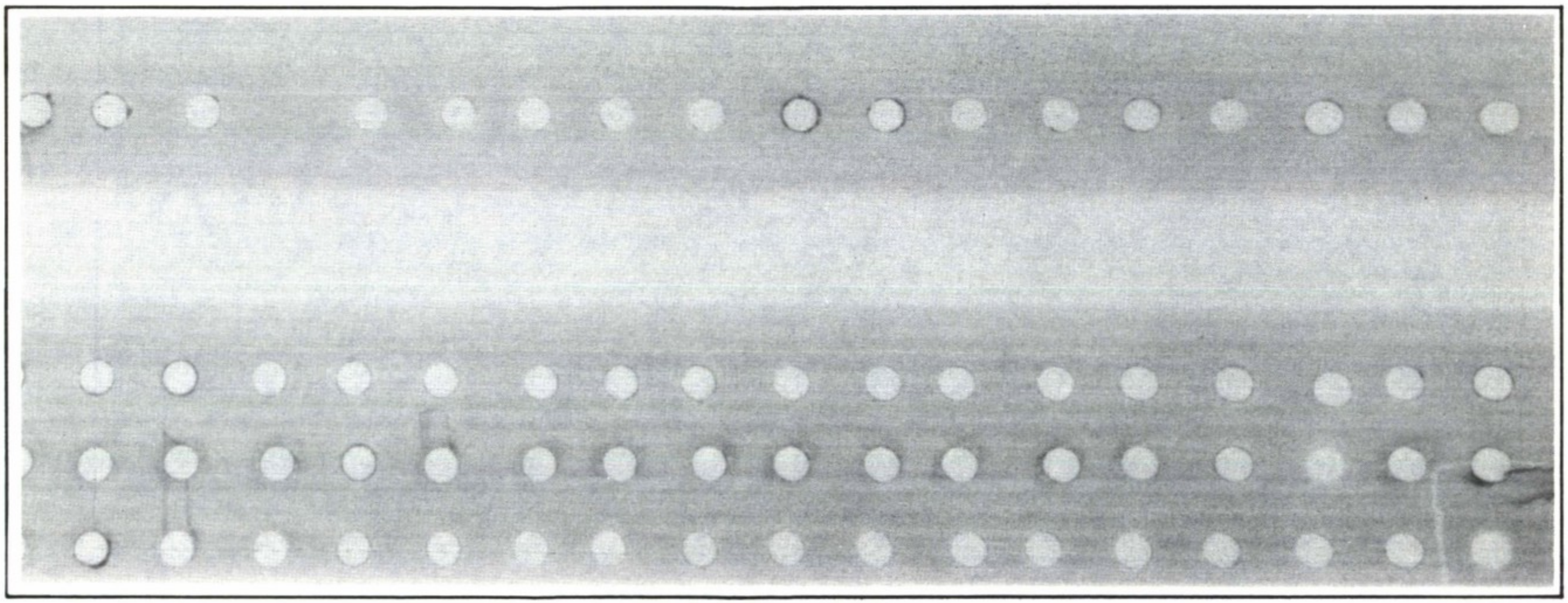

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Figure 7-30 Tracer-Radiograph of Ultrasonically Drilled Holes in Graphite-Boron/Epoxy Panels (Test C)

MATERIAL	THICKNESS, IN.	DRILL TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
KEVLAR/ EPOXY	0.118	0.250 DIA JANCY 2 FLUTE C'BORE W/PILOT	6000	0.001	AVERAGE DE-LAMINATION THROUGH HOLE 5 IS 0.050" MAXIMUM IS 0.120" INCREASING AT LAST HOLE	CANNOT DETECT	DELAMINATION ON ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.118	0.250 DIA JANCY 2 FLUTE C'BORE WITHOUT PILOT	3000	0.001	NO DELAMINATION THROUGH HOLE 8, AVERAGE DELAMINATION THROUGH HOLE 21 IS 0.055 WITH MAX OF 0.100"	CANNOT DETECT	DELAMINATION ON ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.118	0.250 DIA TWIST CARBIDE TIPPED	6000	0.001	RANGE OF DELAMINATION 0.050" TO 0.75"	CANNOT DETECT	DELAMINATION ON ALL HOLES ON ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.118	0.250 DIA FISH TAIL CARBIDE TIPPED	6000	0.001	DELAMINATION RANGE OF 0.055" TO 0.085" ON ALL HOLES	CANNOT DETECT	DELAMINATION ON ALL ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.118	0.250 DIA FISH TAIL CARBIDE TIPPED	3000	0.002	DELAMINATION RANGE ON ALL HOLES 0.090" TO 0.115"	CANNOT DETECT	ENTRANCE DELAMINATION ON ALL HOLES; ALSO EXIT DELAMINATION
KEVLAR/ EPOXY	0.118	0.250 DIA SPADE (SLANT) CARBIDE	6000	0.001	DELAMINATION RANGE ON ALL HOLES 0.080" TO 0.150"	CANNOT DETECT	EXIT DELAMINATION ON ALL HOLES. NEGLIGIBLE ENTRANCE DELAMINATION
GRAPHITE/ EPOXY + KEVLAR/ EPOXY	0.280	0.250 DIA FISH TAIL CARBIDE TIPPED	6000	0.001	DELAMINATION RANGE FOR ALL HOLES 0.050" TO 0.150"	SOME PENETRANT INDICATIONS KEVLAR INTERFERRED	ALL HOLES BADLY DELAMINATED AT EXIT SIDE SLIGHT ENTRANCE DELAMINATION

2199-208B

Figure 7-31 Summary of Non-Destructive Evaluation of Drilled Holes

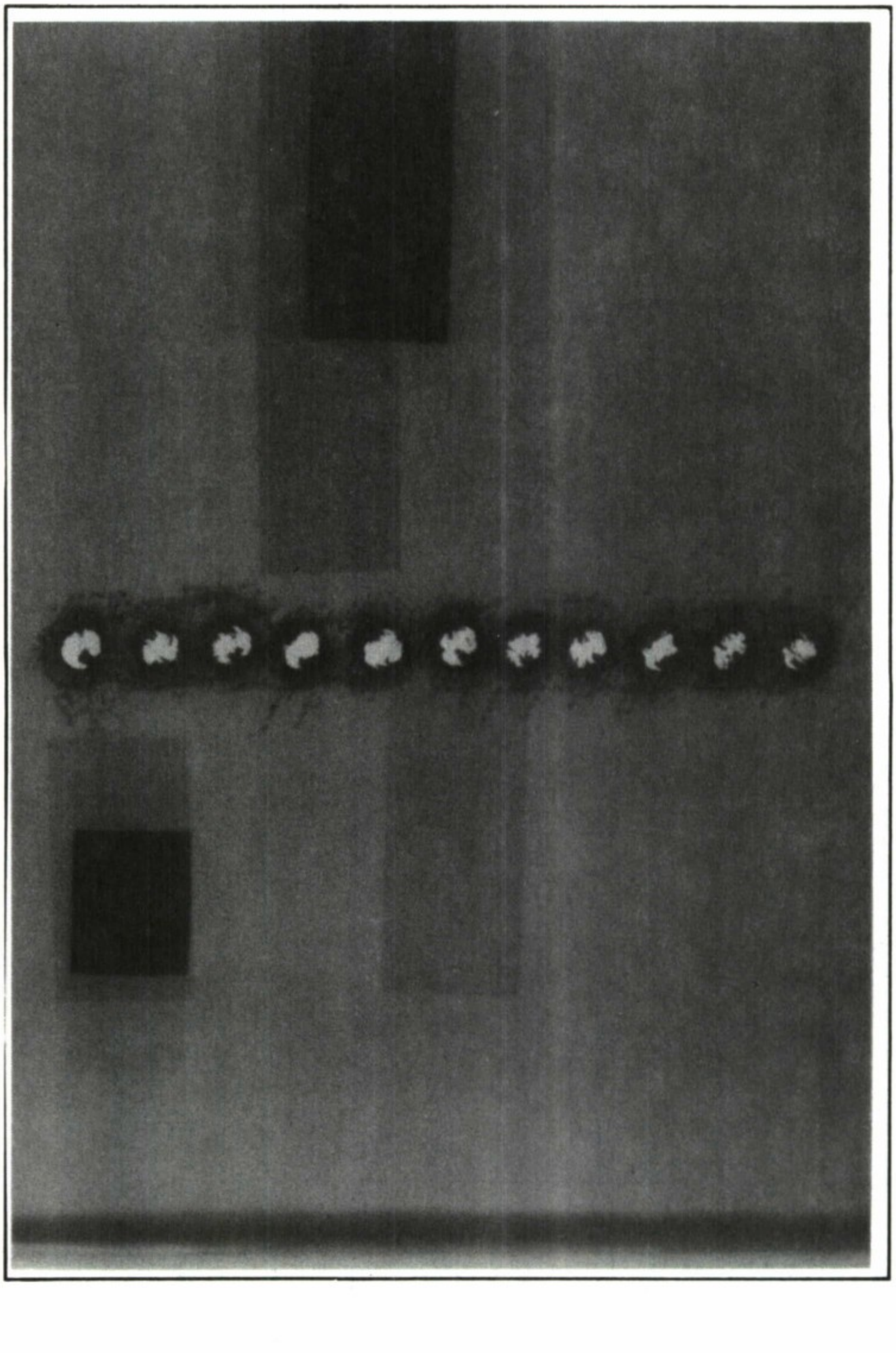

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Figure 7-32 Delaminated Holes in Drilled Graphite-Kevlar/Epoxy Panel (Test No. 13)

MATERIAL	THICKNESS, IN.	C'SINK TYPE	SPEED, rpm	FEED, IPR	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY + KEVLAR/ EPOXY	0.275	2 FLUTE CARBIDE COUNTERSINK Z114105 DRILL/ C'SINK	2400	0.002	INTERFERENCE FROM KEVLAR	INTERFERENCE FROM KEVLAR	ENTRANCE SIDE OF COUNTER SUNK HOLE BADLY FRAYED + SPLIT
GRAPHITE/ EPOXY + FIBER-GLASS/ EPOXY	0.260	2 FLUTE CARBIDE COUNTERSINK Z114105 DRILL/C'SINK	2400	0.002	LITTLE DELAMINATION 0.005	NO SIGNIFICANT INDICATIONS	SLIGHT SURFACE DELAMINATION ON SOME HOLES. COUNTER SUNK AREAS LOOK CLEAN
FIBER-GLASS/ EPOXY	0.125	2 FLUTE CARBIDE COUNTERSINK Z114105 DRILL/ C'SINK	2400	0.002	LITTLE DELAMINATION 0.005"	NO SIGNIFICANT INDICATIONS	SLIGHT SURFACE DELAMINATION ON VERY FEW HOLES.

2199-210B

Figure 7-33 Summary of Non-Destructive Evaluation of Countersunk Holes

MATERIAL	THICKNESS, IN.	COUNTERBORE TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY	0.270	3 FLUTE CARBIDE TIPPED	2400	0.002	NO FLAWS DETECTED	GOOD	GOOD CLEAN COUNTER BORE
GRAPHITE/ EPOXY	0.270		2400	0.001	NO FLAWS DETECTED	GOOD	GOOD CLEAN COUNTER BORE
GRAPHITE/ EPOXY	0.270		4800	0.0005	SPORADIC DELAMINATION ON A FEW OF THE HOLES 0.020" – 0.050"	GOOD	GOOD CLEAN COUNTER BORE
GRAPHITE/ EPOXY + FIBER-GLASS EPOXY	0.270		3600	0.001	SLIGHT DELAMINATION ON SOME HOLES 0.200" - 0.040"	GOOD, NO SIGNIFICANT INDICATIONS	SOME ENTRANCE DELAMINATION ON A FEW OF THE 25 COUNTER-BORE HOLES.
GRAPHITE/ EPOXY + KEVLAR EPOXY	0.270		3600	0.001	KEVLAR INTERFERRED WITH METHOD	KEVLAR INTERFERRED WITH METHOD	TOP SURFACE OF ALL COUNTER BORES BADLY FRAYED; DIFFICULT TO EVALUATE. NO DELAMINATION SEEN
FIBER-GLASS/ EPOXY	0.145		3600	0.001	NO DELAMINATION TO 0.020" DETECTED	GOOD	ALL HOLES LOOK GOOD; SOME SLIGHT DELAMINATION ON ENTRANCE SIDE OF COUNTER BORE HOLE.

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Figure 7-34 Summary of Non-Destructive Evaluation of Counter Bored Holes

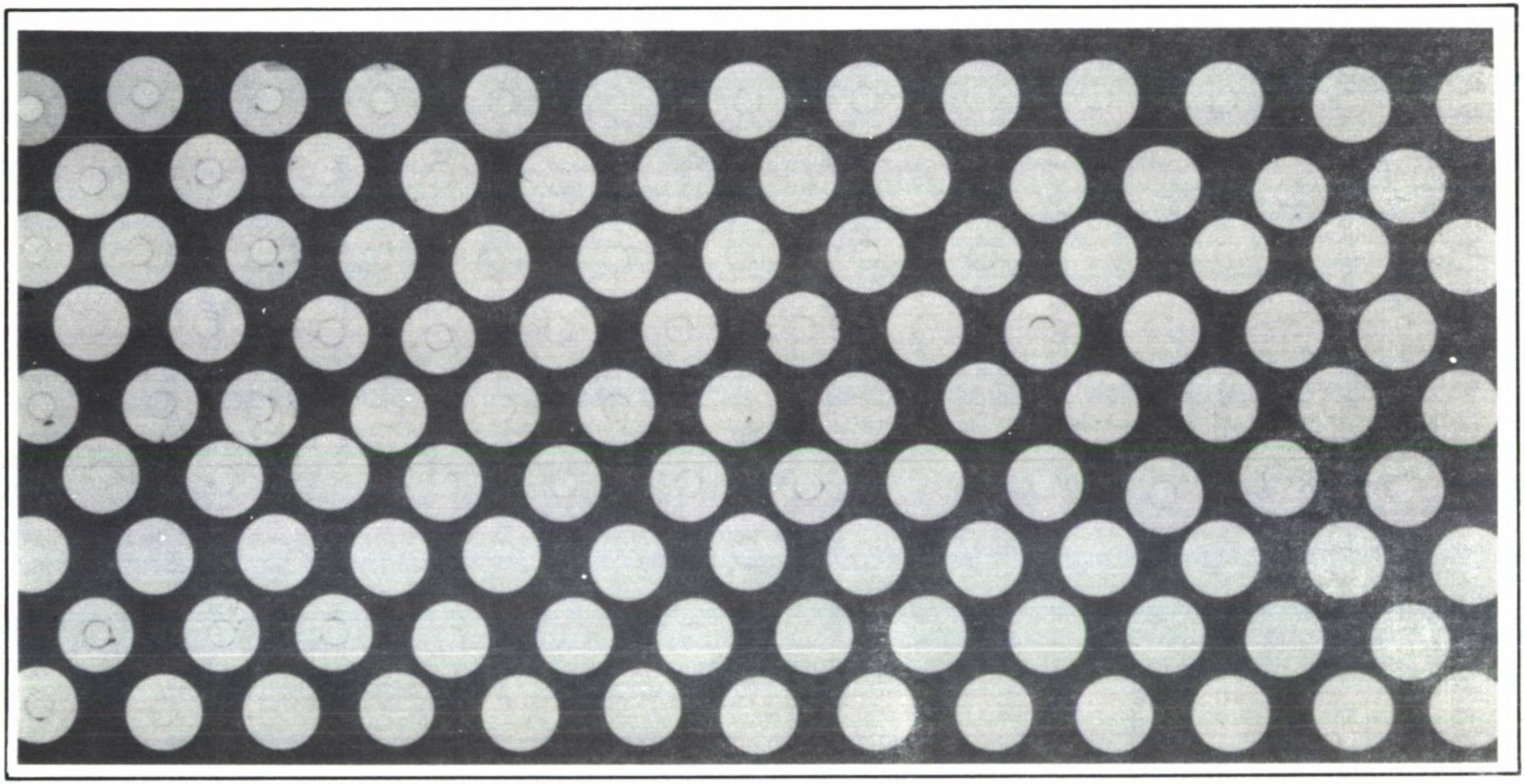

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Figure 7-35 Tracer-Radiograph of Counterbored Fiberglass/Epoxy Panel microcracks and fiber pullout must be detected. In the event that small flaws such as microcracks must be detected in holes, penetrant and boroscopy methods should be used. These methods are time-consuming and costly. Parts should be designed so that these flaws will not critically affect the performance of the composite structure. In general, tracer-radiography should be used initially for all hole or edge evaluations together with visual examination of the area. In the event that more detailed evaluation of the area is required, penetrant and boroscopy techniques should be used. Penetrant inspection can give many false positive indications in holes and, to a lesser degree, along edges. Kevlar composite materials interfere with tracer-radiography, penetrant inspection and visual evaluation of the composite.

7.3 TASK 3 - DEVELOPMENT OF AUTOMATED NDE PROCESS

Integration of the selected NDE methods into an automated inspection system was accomplished in the last phase of the program. The nondestructive method selected for system integration from all those evaluated was tracer-X-ray fluoroscopy employing an image-enhanced video scanning technique. In general, this system consists of a specially designed low-voltage X-ray generation source and a solid-state, TFI-designed, high-resolution image converter with TV readout, including remote control focusing (see Figure 7-36). This system was physically attached to the Grumman-developed Five-Axis Drilling Fixture (Figure 7-37). This computer-directed drilling fixture has the capability to locate and drill holes in complex metal or composite parts with the aid of an advanced computerized scanning technique. The attached NDE system was designed to inspect the drilled holes automatically and it satisfactorily completed that assignment. The tracer material was applied manually, since an automated tracer material feeding system was not within the scope of this program.

7.3.1 System Design

The basic system concept is to use a liquid trace material on composite edges and holes to identify and locate cracks, delaminations and other flaws resulting from cutting machining or drilling those composites. The trace material, 1,4 diiodobutane, (DIB) has a chemical formula ($I(CH_2)_4I$) and a specific gravity of 2.3. Its unique characteristic is that it absorbs X-radiation such that after penetration into open

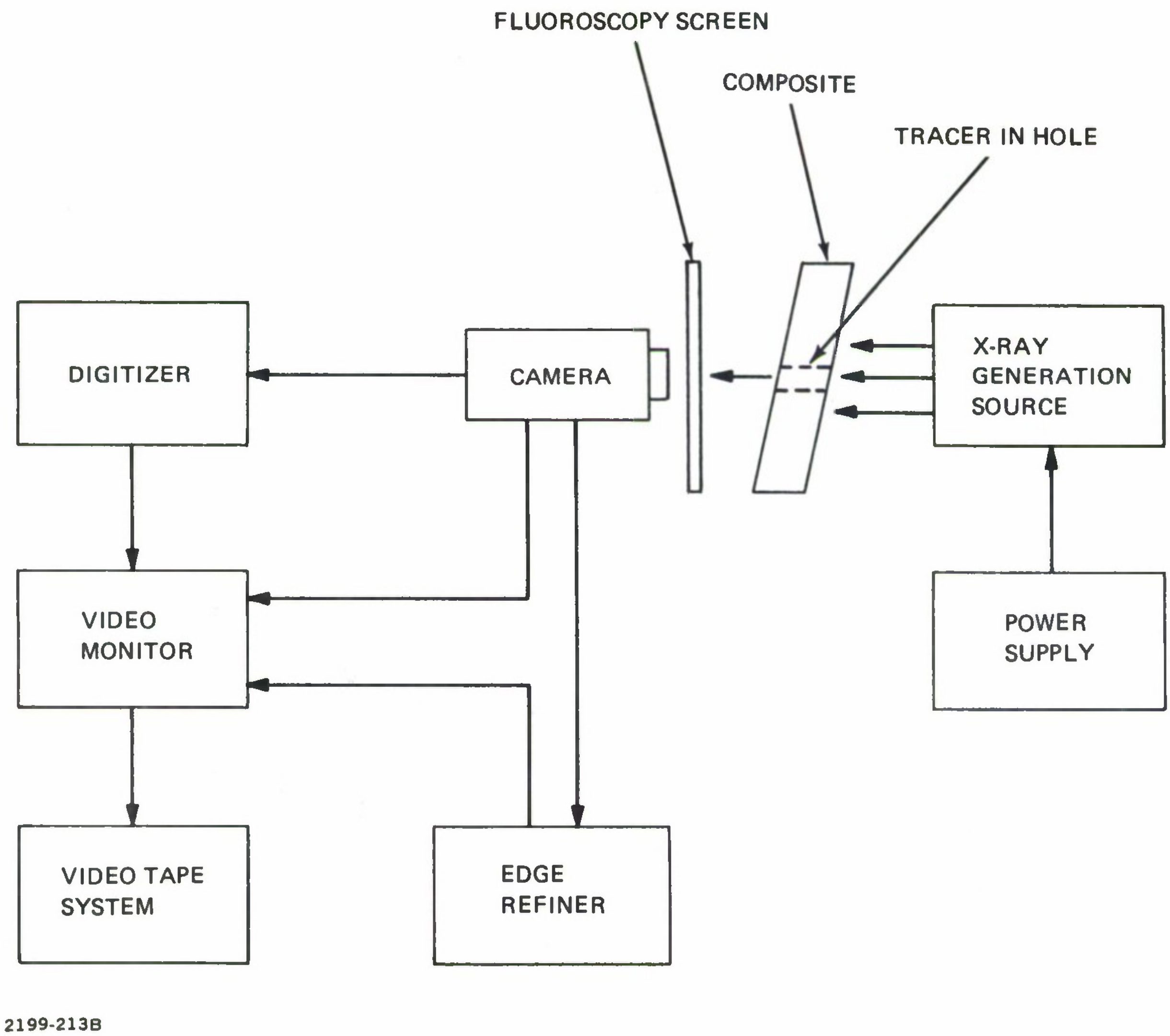

Figure 7-36 Real-Time Composite Edge and Hole Flaw Detection System

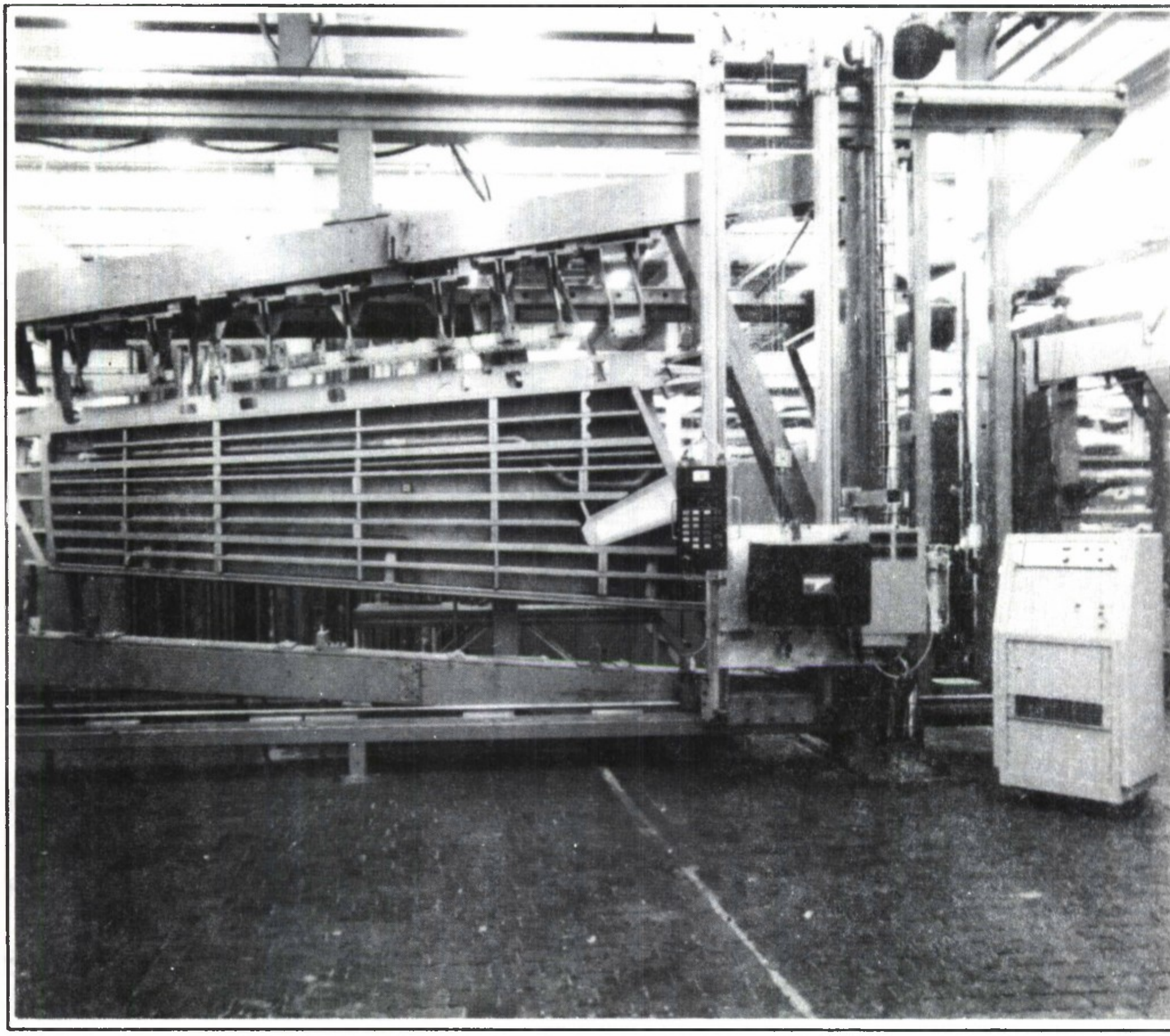

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Figure 7-37 Grumman-Designed Automatic Five-Axis Drilling Fixture composite cracks and delaminations, it detects and locates these flaws by outlining the flaw shape and size (see Figure 7-38). Important considerations in the effectiveness of this tracer material is its nontoxicity, speed of evaporation and high X-ray absorption.

7.3.1.1 Portable X-Ray Generation Source - The equipment used for the source of radiation was the TFI Corporation Hot Shot (Figure 7-39), a portable X-ray unit with a beryllium window that allows emissions of "soft" long-wavelength radiation for radiography of materials of low density such as composites. The specifications for the unit are 10-110 kv, 5 ma, 0.5 mm-focal spot, beryllium window tube, 38° beam, 110 Vac, 60 Hz, stepless voltage and amperage. The voltage used during the testing with the Five-Axis Drilling Fixture was 35-40 kv at 3 ma. The resulting scatter from the composite and lead shielding was a maximum of two MR at 15 feet, showing the safety of the system and its ease of use near personnel.

7.3.1.2 Workpiece - The part used for the system demonstration was a production graphite/epoxy composite sine-wave beam (Figure 7-40) which was mounted on the frame of the Five-Axis Drilling Fixture. Holes were drilled in the part in areas where production holes would be placed. The composite structure was then examined visually for obvious damage and then subjected to the automated tracer impregnation and NDE examination.

7.3.1.3 Image Processing System - The fluoroscopic images can be analyzed by using image enhancement. The image-processing system used in this program consisted of a combination of hardware and software interfaces that have been under development since 1970. All images processed by the system are viewed through a camera and are then analyzed by the following hardware sections of the image-processing system:

- Edge Refinement. This procedure emphasizes edges of images and eliminates backgrounds for easier recognition of boundaries, lines, and fine structures. Edge refinement is performed by the analog computer portion of the image-processing system. The computer permits the derivative of the video signal to be measured and visually displayed on the television monitors. This derivative signal can be mixed with the normal video in varying degrees for optimum analysis. Edge line widths can be

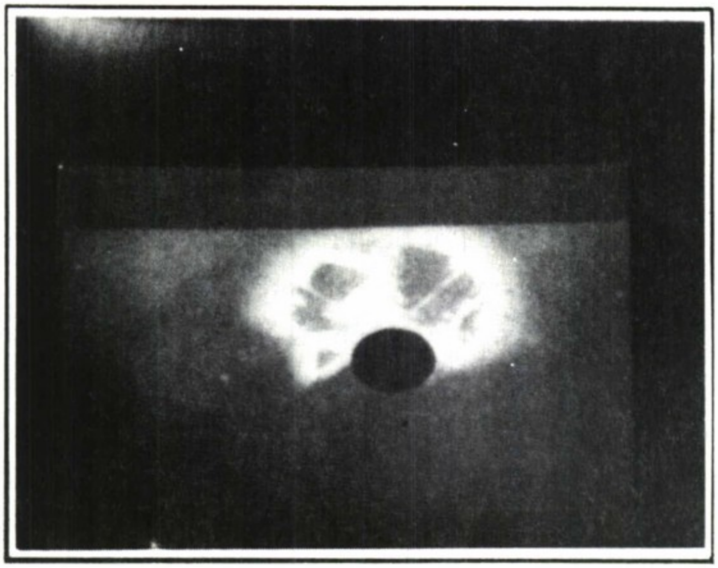

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Figure 7-38 Outline of Delamination from Edge of Hole as Shown by DIB Tracer

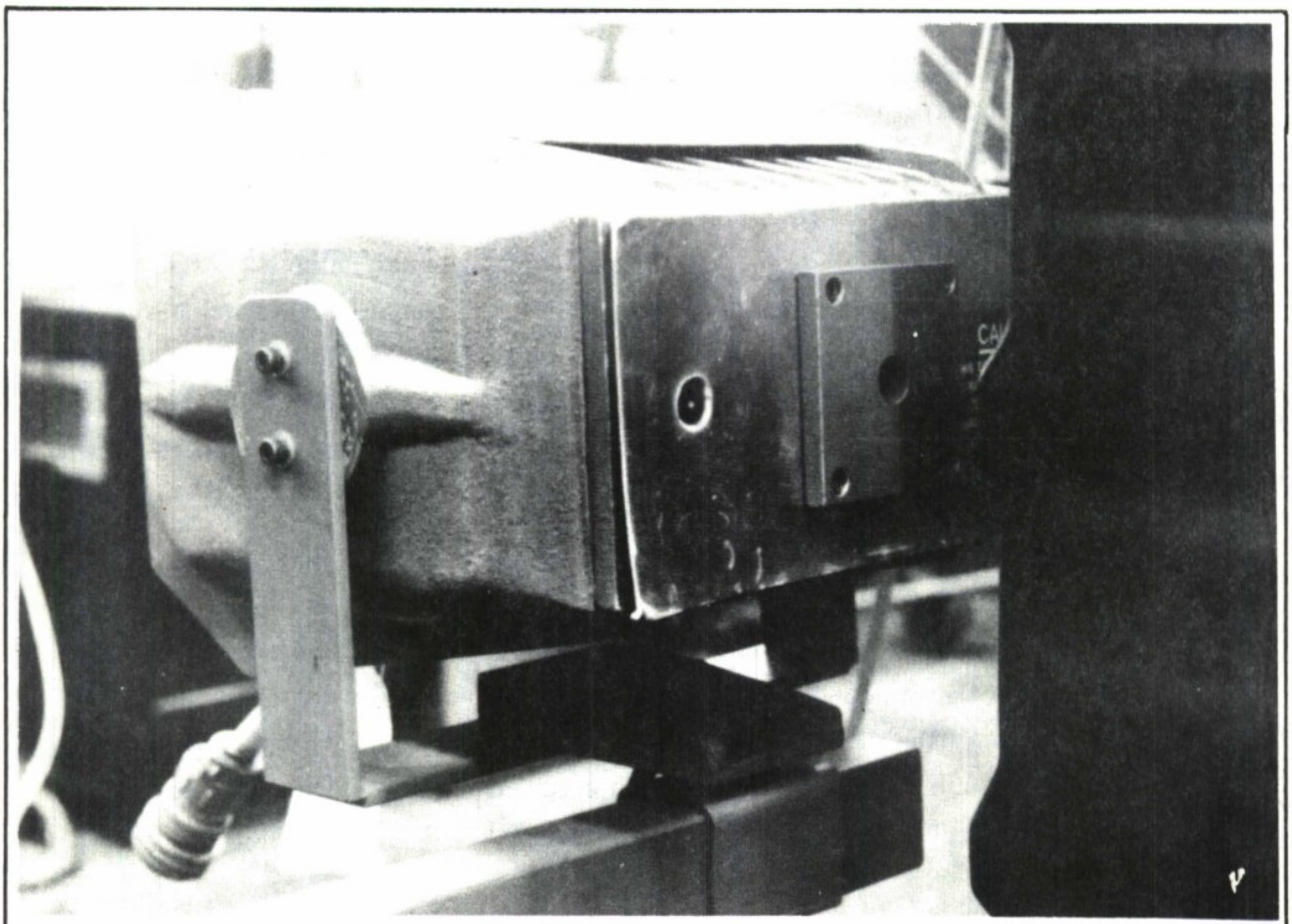

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Figure 7-39 Portable X-Ray Generator on Five-Axis Drilling Fixture

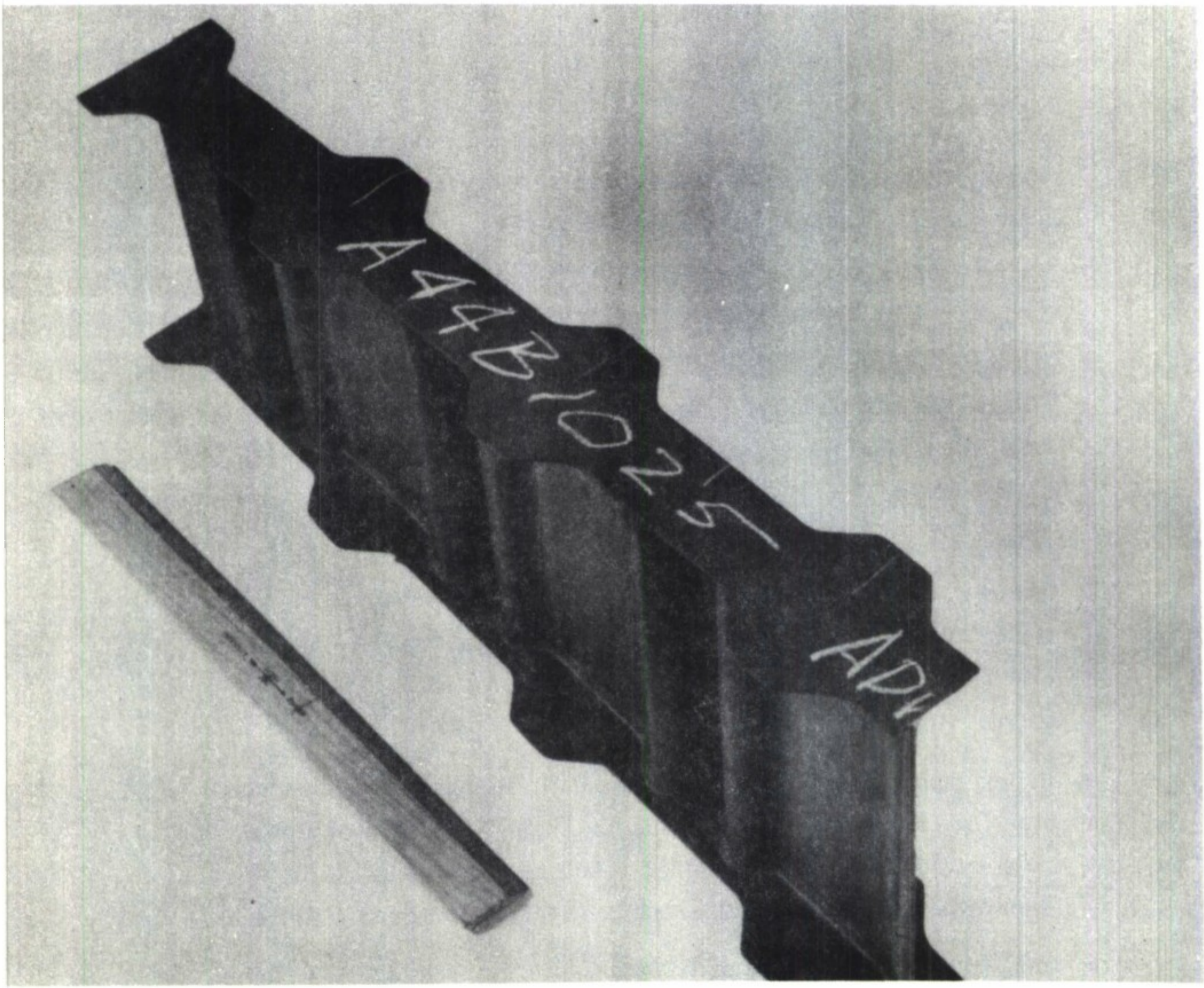

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Figure 7-40 Graphite/Epoxy Sine-Wave Beam Used for Demonstration of Automated Tracer – Fluoroscopy NDE System controlled and adjusted from very thick to narrow for maximum visibility of fine details. Images may be refined during positive or negative viewing.

- Color Assignment. When color assignment is applied, colors are assigned to density ranges to permit easy identification of contours and density boundaries. Color assignment is performed by a logarithmic circuit that electronically analyzes the photographic density of the image being viewed and classifies the densities into twelve discrete colors. These colors allow density contours to be analyzed and, when performed in combination with edge refinement, border areas are further accentuated.

- Density Profiling. This capability provides a graphic display of film density values along a vertical cross-section of the image. With an X-ray, film density can normally be related to changing tissue thickness or density. The profiler is more sensitive to these changes and density than the human eye and it can reveal abnormal or abrupt tissue changes not visible through normal image viewing.

- Micro-Measurements. An optical micrometer in the system has a sensitivity of ±.001 mm on the viewing monitor.

- Dynamic Focusing. Dynamic focusing is a procedure utilized in combination with edge refinement. During edge refinement with mixes of 50% or greater, the sensation of depth increases. Variations in the focus of the image during these refinements will section an image being viewed. This effect can be related to viewing a particle on a slide through a microscope and varying the focus.

- Radiographic Deblurring. This is a digital technique that reduces the blurring (penumbral) effect caused by the physical characteristics of the focal spot in the X-ray machine, resulting in an image which would have been produced had the radiograph been taken with a point source.

- Image Identification Textural Features. This is a digital technique that analyzes textural features based on gray tone spatial dependencies so that these can be used in identifying objects or regions of interest in an image.

- Histogram Modification Techniques. This is a digital technique that uses a non-linear position invariant transformation of the gray level scale, effectively transforming an X-ray image with a heavily biased histogram (such as a mammogram) to a flat, equalized histogram. This technique is currently being modified to increase edge and textural information in the enhanced image.

- Edge Detection Techniques. These are digital techniques that utilize optimal approaches to edge detection, including a Hueckel operator method for finding which edge elements will best fit the intensities in a given region, and various linear and non-linear parallel edge detection approaches.

- Laplacian and Gradient Analysis. This is a digital technique that refines edges of objects in the image and makes the shapes and details in the image more conspicuous and easier to analyze.

- Contrast Refinement. This is a digital process that refines the magnitude or brightness differences between adjacent parts of the image, thereby making the image more readily visible.

- Spatial Filtering. This is a digital technique that separates an image into its high- and low-frequency components. Low-pass filtering eliminates high-frequency interference lines and textures in an image. High-pass filtering can be used to refine images by removing the low-frequency changes caused by Vignetting or uneven illumination.

7.3.2 System Demonstration

The display system (Figure 7-41) shows the fluoroscopy image of the DIB Tracer material used on composite structures. Figure 7-42 illustrates the results of using DIB tracer on drilled graphite/epoxy holes. Figure 7-42a shows the fluoroscopy image of the composite hole prior to application of the DIB tracer. There are no flaws indicated. After application of the tracer, delamination and back surface breakout become apparent (Figure 7-42b). Using the edge enhancement technique, the flaws surrounding the holes become even more pronounced (Figure 7-42c). Edge enhancement of the image allows for better computer pattern recognition should that method be used in an automated system.

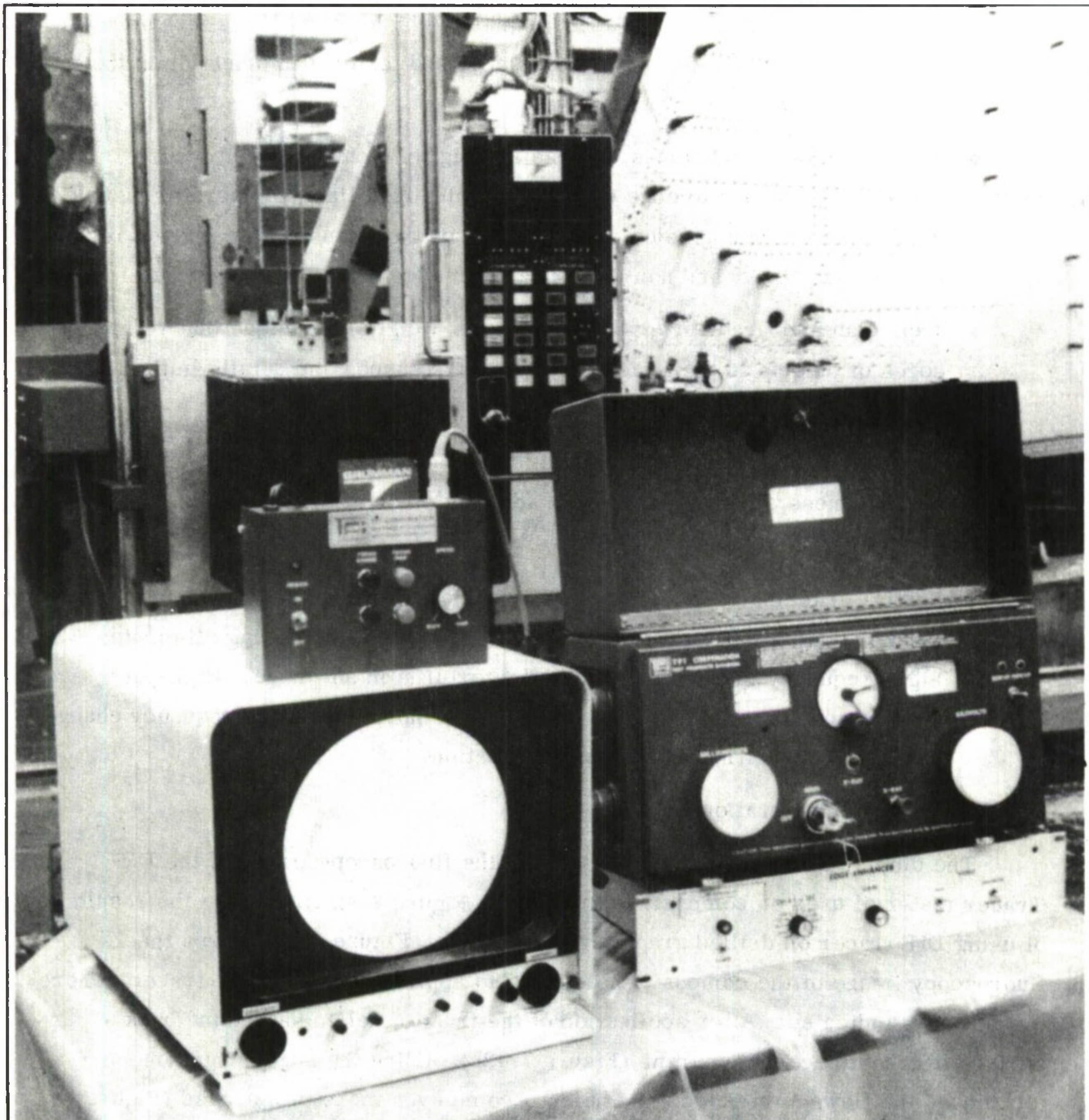

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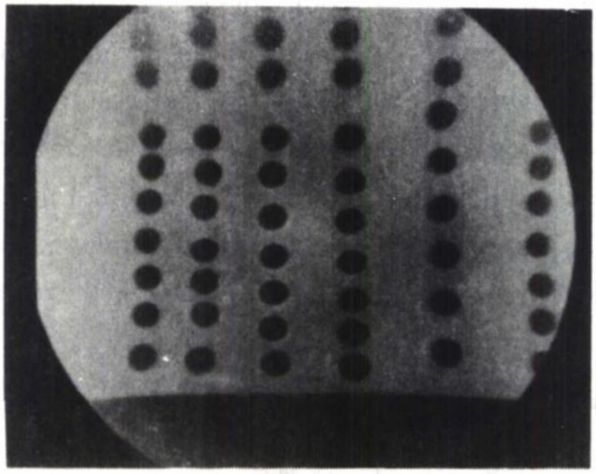
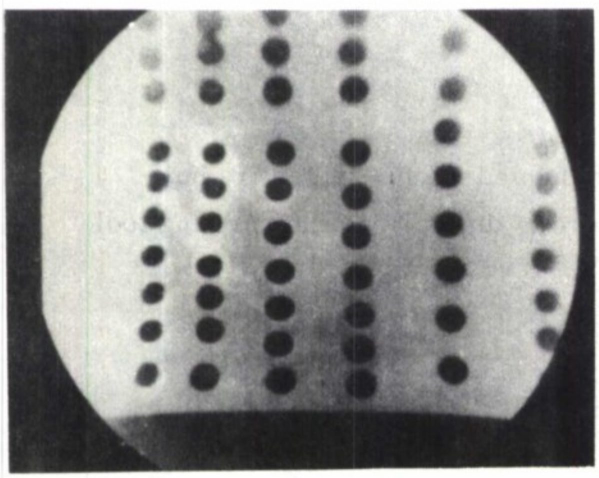
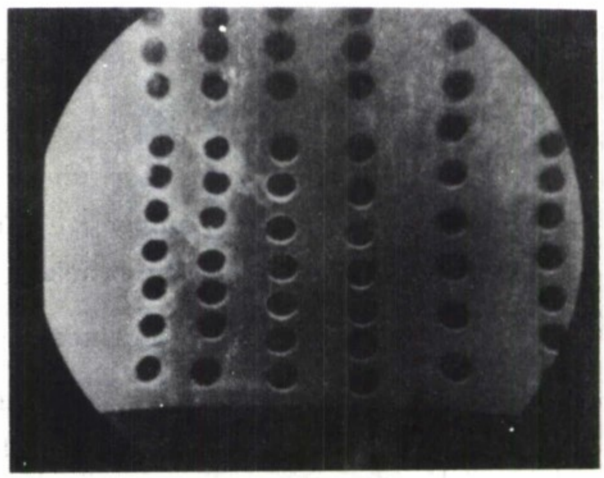
Figure 7-41 Video Display System to Show Fluoroscopy Image from Tracer-Impregnated Sine-Wave Beam



a. Initial Image



b. Image with DIB Tracer



c. Image with DIB Tracer and Image Enhancement

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Figure 7-42 Fluoroscopic Image of Drilled Graphite/Epoxy Panel at 15 KV.and 3 MA

The X-ray generation source and TV Camera of the automated NDE System was attached (Figure 7-43) to the moveable head (Figure 7-44) of the Five-Axis Drilling Fixture. This moveable head can traverse the fixture in an X-Y direction, and for the purpose of this program, traversed along the length of a graphite/epoxy sine-wave beam while examining previously drilled holes in that structure by means of the attached radiographic system (Figure 7-45). The system automatically scanned each hole after the application of the tracer material and showed several delaminated holes not expected in the sine-wave beam. The delaminations were detected while the part was on the fixture and evaluated at that time. The DIB tracer material evaporated relatively quickly and left no trace, thereby showing the ease of material cleanup.

The concept of using tracer fluoroscopy coupled with automated video scanning was adequately demonstrated on an actual production part. The NDE System integrated with the Five-Axis Drilling Fixture showed the practical feasibility of the approach with excellent reliability. Video scanning of the structure is also recommended as part of the automated inspection system, since it can eliminate gross delaminations and breakout in the material.

7.4 COST ANALYSIS OF NDE TECHNIQUES

7.4.1 Manual Techniques

7.4.1.1 Borescoping - The scope must be manipulated to view the entire hole surface. Interpretation is subjective, since there is difficulty in interpreting tool marks, resin/fiber pullout and cracks.

Time per hole is three minutes.

7.4.1.2 Penetrant Inspection - Penetrant inspection can lead to many false indications and result in extensive verification time. This method will detect most surface flaws generated as a result of cutting, drilling or machining of composites.

Time per hole is three minutes.

7.4.1.3 Visual Examination - Visual evaluation with white light and 10X magnification is also subjective method. Minor resin tear-out gives the impression that small delaminations are present when none are.

Time per hole is three minutes.

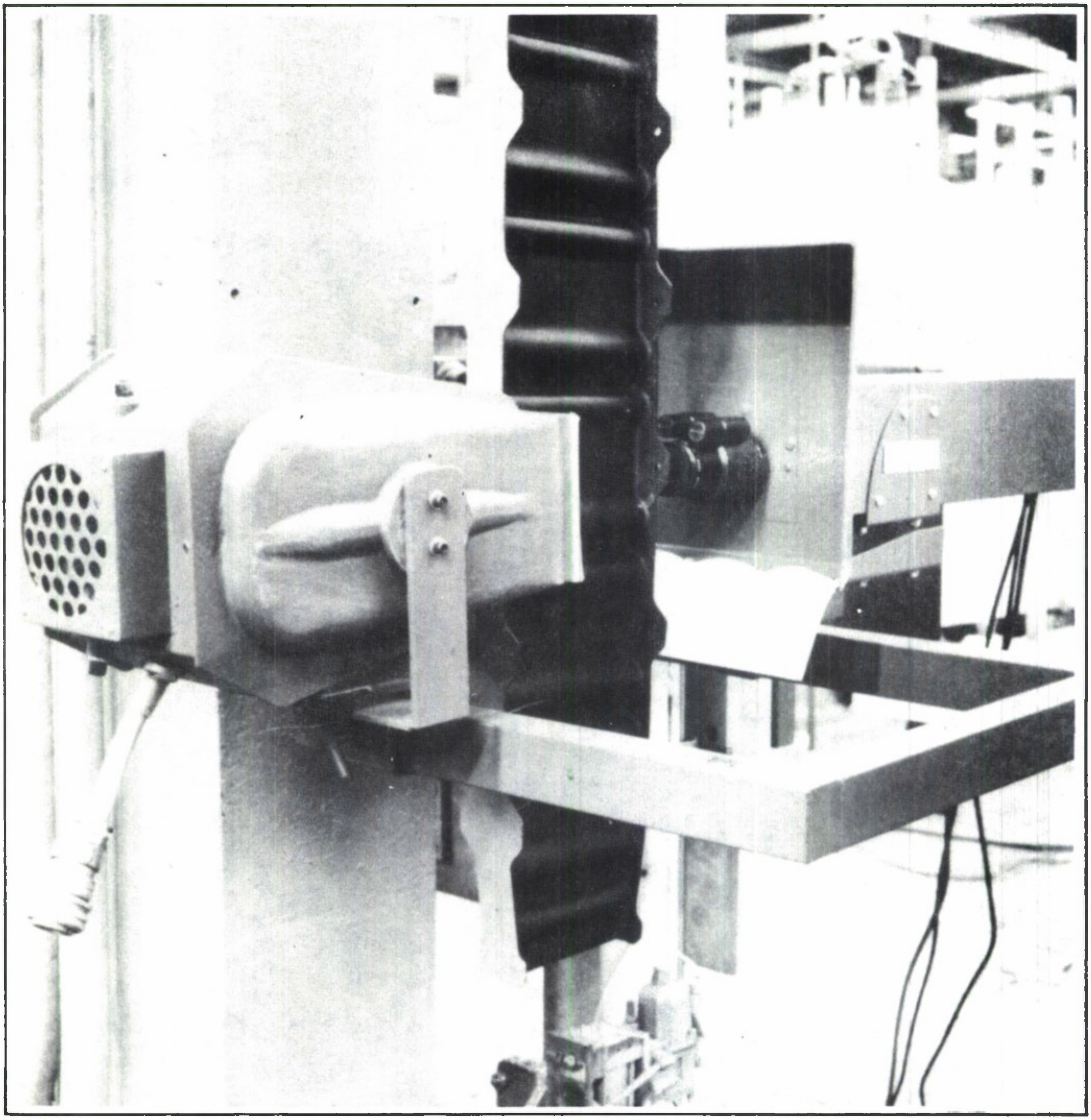

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Figure 7-43 Diametrically Opposed X-Ray Generator and TV Camera on Five-Axis Drilling Fixture

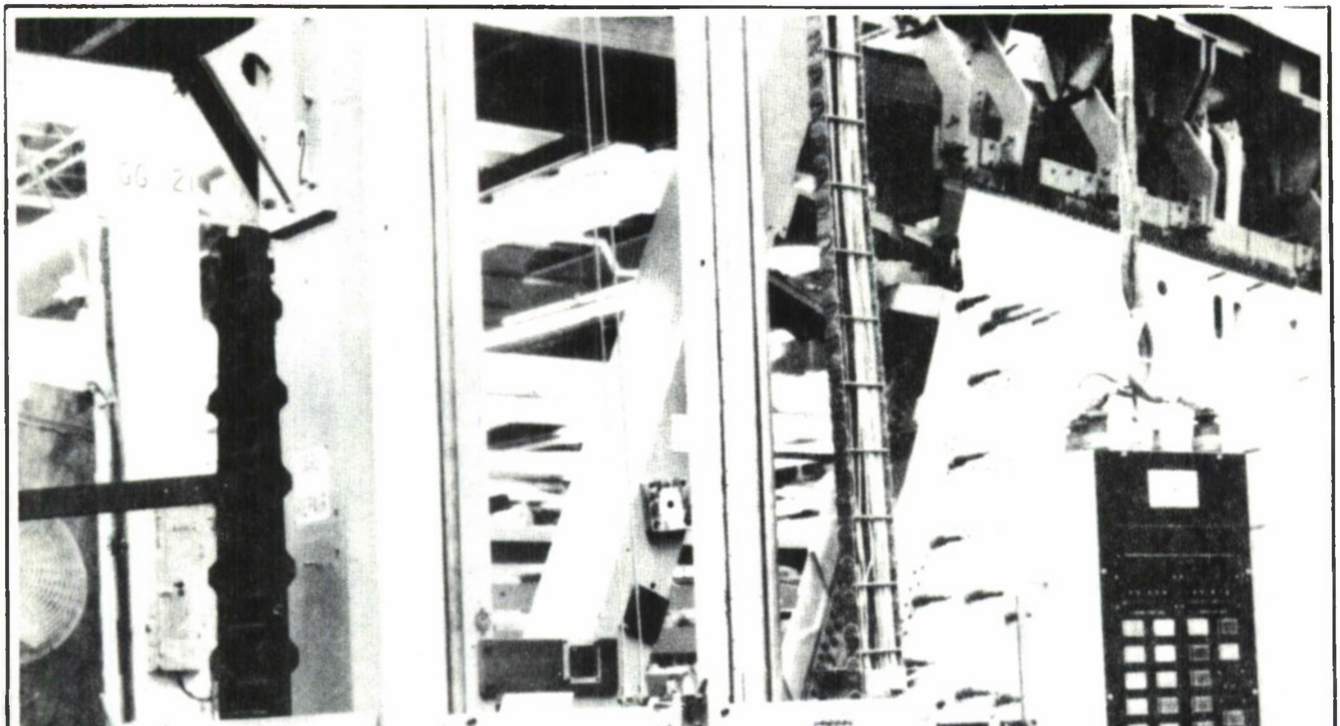

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Figure 7-44 Movable Head of Five-Axis Drilling Fixture

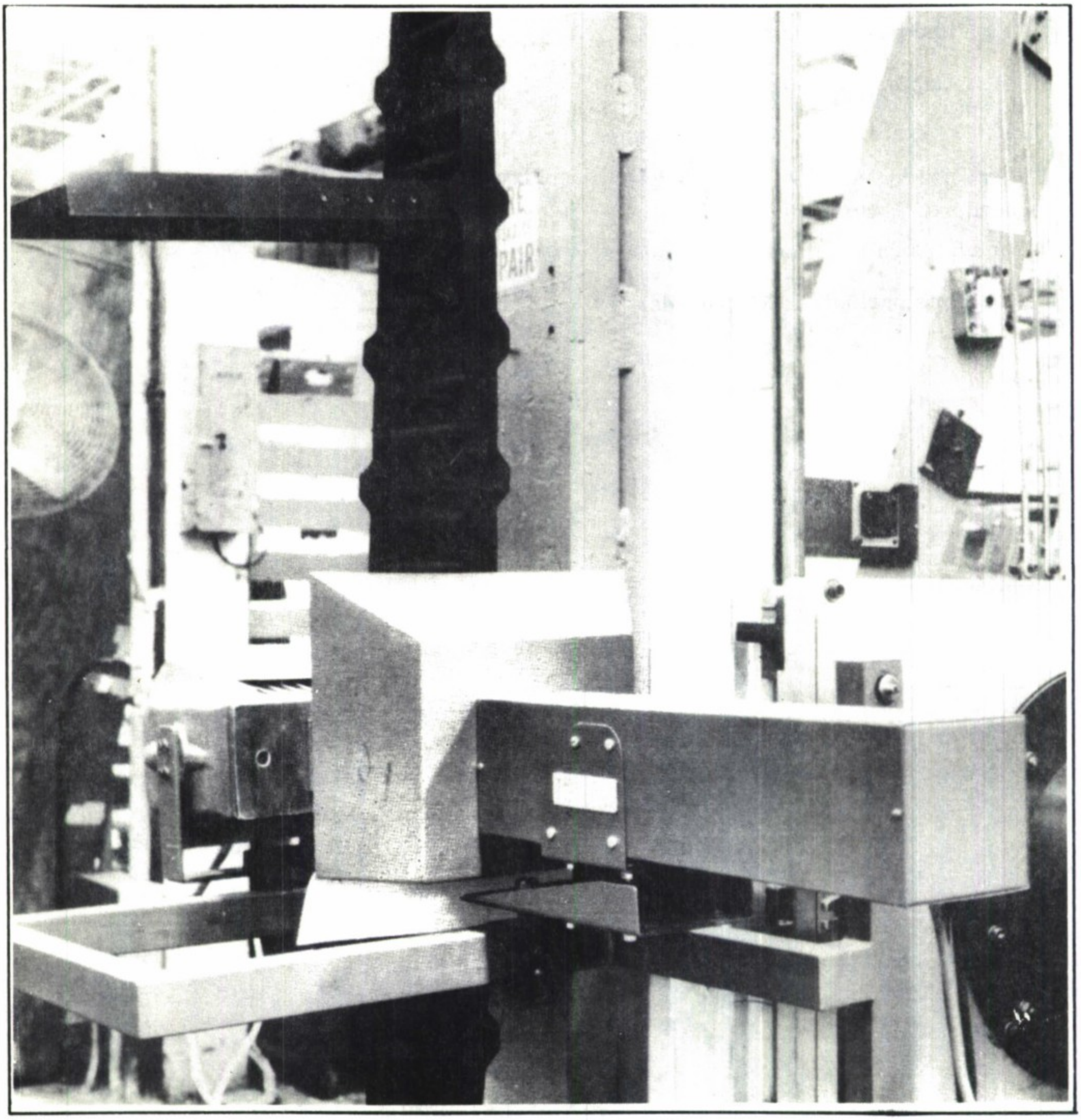

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Figure 7-45 Tracer Fluoroscopy NDE System Moving Vertically along Graphite/Epoxy Sine-Wave Beam

7.4.1.4 Tracer-Fluoroscopy - Depth of hole and detection reliability is high with tracer-fluoroscopy. Since clean-up is not required, time is only expended in applying the tracer material and viewing the suspect area.

Time per hole is one minute.

7.4.2 Automated Method

7.4.2.1 Tracer-Fluoroscopy - Integrating the NDE system with an automated positioning system such as the Five-Axis Drilling Fixture greatly speeds up the evaluation procedure. Automated tracer impregnation methods with fluoroscopy viewing immediately after offers an excellent real-time inspection system.

Time per hole is 35 seconds.

Appendix A

CALCULATION OF PROBABILITY AND CONFIDENCE LEVEL

In order to properly assess the "confidence level" or reliability of a set of data, it must be expressed in terms of probability and in a confidence of that probability. In this program the specimens were evaluated with nondestructive evaluation techniques which correctly located the flaws in each specimen or did not. The data sets then lend themselves to the Binomial Probability Distribution:

$$P(y) = C_y^n P^y q^{n-y}$$

where:

$P(y)$ = Probability distribution for random variable (y)

N = Number of trials

P = Probability of a sample point success

q = Probability of a sample point failure $(1-p)$

C_y^n = Number of N objects taken y at a time.

$P(y)$ may also be stated as follows:

$$P(y) = \frac{N!\, p^y q^{n-y}}{Y!\, (N-Y)!}$$

Since the sampling was done randomly and the number of samples, N, is sufficiently large, the binomial variable, y, will be approximately normally distributed, allowing the areas under a fitted normal curve to approximate the binomial probabilities.

Since it is known that 95% of the area under the fitted curve will lie within two standard deviations from the mean, the binomial probability formula, $P(y) = C_y^n P^y q^{n-y}$ may be used to calculate the probability $P(y)$ that a number of successes would just fall outside the 95% confidence level. By estimating the P in the above formula so as to obtain a value slightly less than 0.05 for $P(y)$, the probability for the experiment may be obtained with a confidence better than 95%.

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